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PROJECT COMPLETION
REPORT NO. W108

Hydrologic Investigation of Small Watersheds in Ohio

Phase I
October 1966 - July 1969

TAIGANIDES

United States Department
of the Interior

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B-005-OHIO
MG 14-01-0001-866

State of Ohio
Water Resources Center
Ohio State University

HYDROLOGIC INVESTIGATIONS OF SMALL WATERSHEDS IN OHIO

TERMINAL REPORT

Phase I: 1966-1969

Principal Investigators

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WATER RESOURCES CENTER
Engineering Experiment Station
The Ohio State University
Project W108

OFFICE OF WATER RESOURCES RESEARCH
U. S. Department of the Interior
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Contract No. 14-01-0001-866

HYDROLOGIC INVESTIGATIONS OF SMALL WATERSHEDS IN OHIO

Phase I: 1966-1969

ABSTRACT

Traditional statistical, analytical techniques and deterministic models were used to study runoff phenomena from agricultural and strip-mined areas at the North Appalachia Experimental Watersheds Station near Coshocton, Ohio. Agricultural land use and surface strip mining were found to influence the hydrology of the watershed and the physical and chemical quality of the runoff water. Peak runoff rates were predicted using the standard formulas and with the Stanford and Purdue computer models. The latter were modified and input parameters had to be developed before using them. A basic study to better understand the fundamental phenomena and the mechanics of runoff were studied. Small watersheds were defined as watersheds whose hydrology is modified with agricultural and industrial practices on the land during a year's time.

KEY WORDS

<u>Descriptors</u>: Agricultural Watersheds/Small Watersheds/Demonstration Watersheds/Storm Runoff/Time of Concentration/Corn Belt/ Appalachia/Hydrologic Models/Computer Models/Simulation

FCST Category: II-A

MATCHING GRANT

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Office of Water Resources Research
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to

Water Resources Center
The Ohio State University
Columbus, Ohio 43210

HYDROLOGIC INVESTIGATIONS OF SMALL WATERSHEDS IN OHIO

Phase I: 1966-1969

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Heggie N. Holtan	Director	USDA Hydrograph Laboratory

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FOREWORD

This has been a multidepartmental, interdisciplinary research project involving students, faculty, and researchers from two branches of the U. S. Department of Agriculture. Fortunately, it has been a happy experience despite the large number of people involved and the breadth of the studies undertaken.

The report was compiled from work that resulted in five Master of Science theses (Balk, 1968; Briggs, 1969; Simmons, 1968; Sopak, 1969, Wicks, 1968), and one Ph.D. thesis (Merva, 1967). The major adviser for all of the Masters candidates was Dr. Ricca, Civil Engineering; the major professor for G. Merva was Dr. Schwab. The work on the use of the Purdue model was carried out by several research associates (Nordstedt, Sarkar, Nwa) and two upper level engineering students. The other faculty member who was involved in the development and implementation of the project was Dr. Hamdy.

We are extremely grateful for the fine cooperation, inspiration and help we received from the staff of the North Appalachia Experimental Watersheds. We particularly want to recognize Mr. L. L. Harrold, Cfficer in Charge and Adjunct Professor of Agricultural Engineering, who also served on the various examining committees; Dr. W. Edwards, Soil Physicist who provided us with information, data and advice; Mr. J. McGuinness, who aided in the analysis and interpretation of the data. In the early stages of the project, Messrs. C. Amerman and J. Urban were of much assistance.

This research was also coordinated to some extent with the staff of the USDA Hydrograph Laboratory in Beltsville, Maryland. The Director of the Laboratory, Mr. H. M. Holtan, and some of his staff helped coordinate the computer modeling studies in setting up experiments for the collection of data applicable to both their research and our project.

You might be interested to know what has happened to the students who received degrees from this project. Mr. Balk accepted a position in water resources planning with a consulting engineering firm in Ohio; Mr. Briggs went with the Shell Oil Company in Ohio; Mr. Simmons was employed by the U. S. Forest Service in Wisconsin; Mr. Sopak returned to his native country, Thailand, to work with water resources agencies; Mr. Wicks is associated with an engineering consulting firm in Ohio; Dr. Merva joined the faculty at Michigan State University.

It is difficult to name everyone without risking ommissions. However, I would like to acknowledge the support and encouragement of Dr. George Hanna who at the time served as Director of the Water Resources Center, and Dr. Robert E. Stewart, who served as Chairman of the Agricultural Engineering Department. The assistance of the OSU Computer Center is also acknowledged.

E. Paul Taiganides
Project Director

Columbus, Ohio

INTRODUCTION

Increased public interest in a watershed approach to water management and control has focused attention on the scarcity of physical data from which engineering, agronomic, and economic aspects of watershed programs are being planned and developed. Data are needed for adequate planning of watershed development and for effective and efficient management of water and soil resources for all agricultural uses of water, as well as related municipal, industrial, and recreational uses.

Most hydrologic data have been collected either from large watersheds or from experimental plots. Adequate data are not available for watersheds of 5 to 50,000 acres in area, and unfortunately present knowledge limits the extension of existing data to watersheds either larger or smaller in size. Since a large number of water resources programs in Ohio are concerned with watersheds in this size range, the lack of data on peak rates and volumes of runoff, limits the progress to be made in these programs.

There are few places in the world where facilities have been developed and small watersheds have been instrumented for the collection of hydrologic data from small watersheds. By small watersheds we mean watersheds whose hydrology can be drastically altered by means of land use practices in a year's time. One of the best equipped and staffed, and certainly one of the oldest such stations, is the North Appalachia Experimental Watershed facility, which is located in Coshocton, Ohio, about 90 miles from the Ohio State University campus, and is operated by the Soil and Water Conservation Branch of the U. S. Department of Agriculture. The station was established in 1937. Data from this station were made available to the project for analysis and interpretation.

The general goal of this study was to investigate stochastic and deterministic models as a means of identifying and evaluating the pertinent parameters affecting runoff from small watersheds. In doing this, we hope to develop information and design criteria for the many water resources development projects being contemplated in Ohio and in the larger physiographic plateau of Appalachia which extends from Pennsylvania down to Tennessee.

Furthermore, this project provided the opportunity for graduate engineering students to participate in an active research program involving several agencies and disciplines.

During the first phase of the project we used statistical techniques to analyze 30 years data that had been collected from several watersheds with good land use and treatment. At the same time we instrumented one of the small watersheds which had been mined and reclamation practices had been initiated on it, to monitor the development of its drainage and hydrology. We then studied the application of traditional runoff formulas on the watersheds that were being investigated, and began to look into mathematical and computer models. We initiated a two-prong approach to the modeling of the watershed; one was basic in nature and the other was more in the applied field. We started looking at the fundamental phenomena associated with the rainfall runoff process, using Ph.D. candidates. At the same time we looked at two models already developed, the Stanford and the Purdue models, with the idea of modifying them sufficiently to test their applicability on the watersheds under investigation.

Simultaneously, we coordinated our efforts with the U. S. Hydrograph Laboratory who were testing their own model on the same watersheds.

This report includes our findings during Phase I. In Phase II we will continue these investigations both in studying the fundamentals of runoff and in further refining the Stanford and Purdue models.

The scope of the project covered by this report was started in October 1966 and was completed in December 1969.

GENERAL DESCRIPTION OF THE STUDY AREA

The data for the studies reported heretofore were obtained from the North Appalachian Experimental Watershed (NAEW) located near Coshocton, Ohio. NAEW was started in 1935 and is being operated by the Soil and Water Conservation Branch of the Agricultural Research Service of the U. S. Department of Agriculture.

Location

The North Appalachian Experimental Watersheds are located about ten miles north of Coshocton, Ohio, in the Muskingum River Basin. The experimental area lies south of the limits of glaciation, at a latitude of 40° 22' North, and within an elevation range of 800 to 1,300 feet mean sea level. This site typifies much of the agricultural land in the unglaciated Allegheny Plateau which covers part of southeastern Ohio, western Pennsylvania, western West Virginia, a portion of eastern Kentucky, and central Tennessee. Figure 1 shows the location of Coshocton in Ohio and the Little Mill Creek Watershed study area; and Figure 2 shows the site map of Coshocton and the Allegheny-Cumberland plateau.

Climate

The precipitation pattern at the study area conforms to the Ohio River Valley Pattern. Summertime rainfall is featured by the convective-type storm usually of high intensity but short duration and covers a small area. Winter precipitation is mainly due to cyclonic-type storms generally of low intensity but long duration and covering a large area. Snowfall is not a major source of precipitation at the station. The average snowfall amounts to 24 inches per year which is about 5 percent of the total precipitation. Based on a 31-year record (1937-68), the average annual precipitation at the station is 37.16 inches and ranges from a recorded minimum of 27.61 to a maximum of 48.92 inches.

During the 25-year period (1937-62), the average mean monthly temperature is 50.3 degrees Fahrenheit. The highest monthly average of maximum temperatures and the lowest monthly average of minimum temperatures are 92.4 and 0.4 degrees Fahrenheit, respectively. The ground is frozen on the average of 57 days per year and frost reaches a depth of about 13 inches.

The growing season amounts to an average of 178 days per year and extends from April 28 through October 23. The distribution of precipitation and temperature during the year is almost ideal for the growth of corn and grasses.

Geology

The bedrock strata of the area consists of the sandstones, shales, clays, limestones, and coal and iron ores of the upper Pottsville, the Allegheny and the lower Conemaugh series of the Pennsylvania system. The strata were eventually elevated above sea level. As a result, the process of weathering developed and valleys and hills were formed. Later crustal movements lead to uplifting of this erosion surface at the time the Allegheny Plateau was formed.

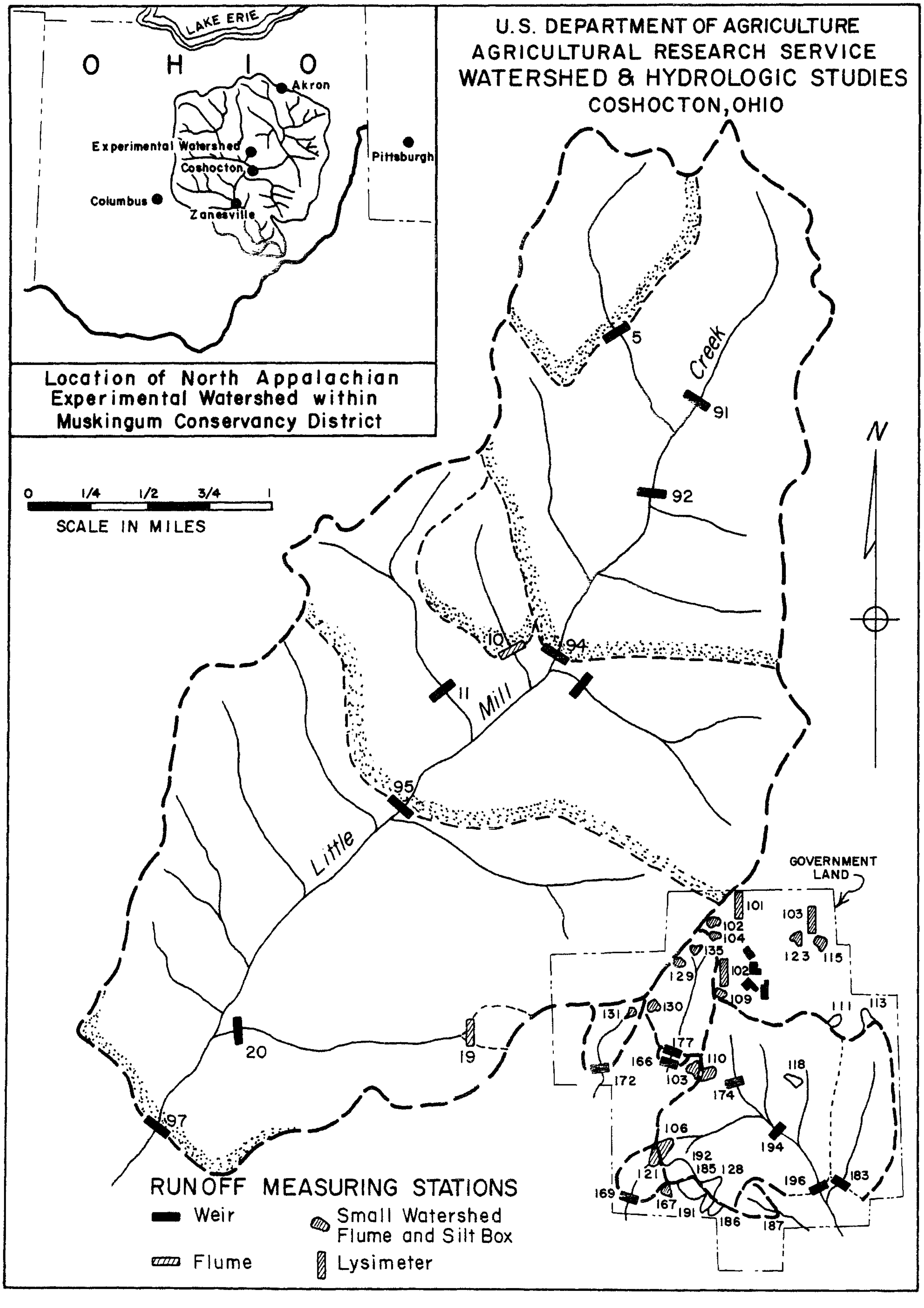

Figure 1. North Appalachian Experimental Watershed.

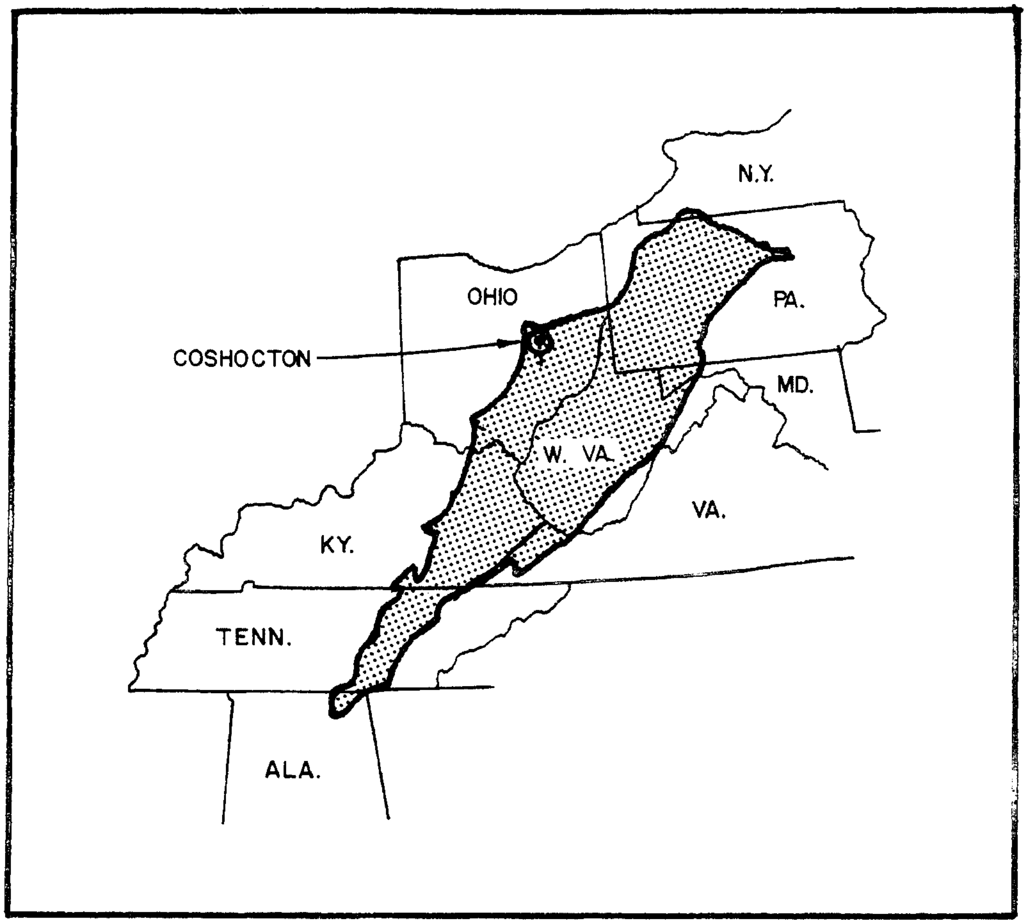

Figure 2. Site Map of Coshocton and the Allegheny-Cumberland Plateau Physiographic Province.

Ice advance during the Pleistocene time stopped a few miles north and west of the study area. This introduced a new factor in the modification of the land surface by filling old valleys and diverting streams so that new valleys and new drainage systems were formed in regions untouched by glacial ice. Harrold, et al. (1962) reported that little change was made in the drainage system of the experimental watersheds and the area immediately south.

The most significant feature of the geologic structure in the study area is the Cambridge Arch. The crest of the arch runs generally north to south. The Cambridge Arch is prominent through most of east-central Ohio; it is not entirely a local occurrence. A typical columnar section of the strata underlying the Coshocton watersheds is shown in Figure 3.

Soils

The most extensive soil* series on the experimental watersheds is the Muskingum, an upland soil developed from sandstone and shale. The surface soil of the Muskingum silt loam is brown to yellowish brown, generally about six to eight inches thick. The subsoil is yellowish brown, contains occasional sandstone and shale fragments, ranges from five to eight feet deep. Surface and internal drainage are good. The chemical characteristic is normally acid. Muskingum loam is derived largely from sandstone and is coarser in texture throughout the profile than Muskingum silt loam. It is rather shallow and contains numerous sandstone fragments.

Physical and Hydrological Characteristics

Table 1 gives data on the physical and hydrological characteristics of the experimental watersheds.

THE INFLUENCE OF LAND USE AND TREATMENT ON THE HYDROLOGY OF SMALL WATERSHEDS

Introduction

In 1938 an experimental program was established on four mixed-cover watersheds at the North Appalachian Experimental Watersheds (NAEW), Coshocton, Ohio to determine the effect of land use and treatment on the hydrology of small mixed-cover watersheds. Harrold, et al. (1962) presented a comprehensive evaluation of the data gathered on the experimental watersheds from 1938 through 1957. However, in much of the analysis the period of record was not of sufficient length to show if statistically significant trends had developed. It was postulated that with an additional ten years of data (1958 through 1967) and some refinements in the statistical methods used in the original study, the influence of land use and treatment on the hydrology of the study, watersheds could be better evaluated. The above postulation was the objective of this study. The statistical methods used were also programmed for the digital computer to facilitate updating.

*Current updating of the soils map of the area may find new names for these soils.

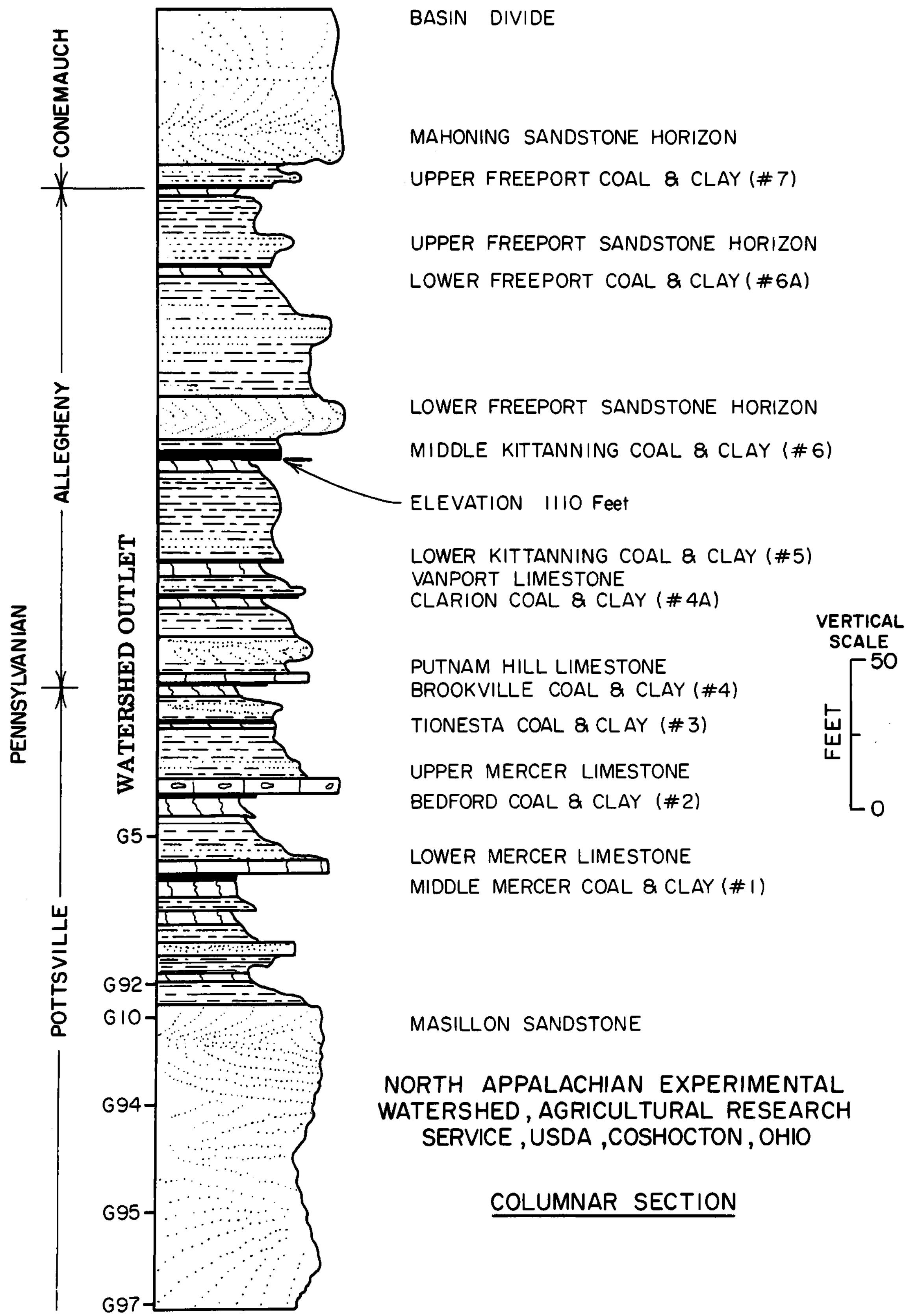

Figure 3. Typical Columnar Section from North Appalachian Experimental Watershed, Coshocton, Ohio. (From Files of NAEW.)

Table 1. Watershed Characteristics

Watershed	Drainage area acres	Length of principal water-course feet	Average slope percent	Aspect	Peak discharge of record		Land Use
					cfs	year	
5	349	4,900	15.5	SE	382	1957	Mixed cover under conser-vation practice
10	122	3,400	16.2	SE	216	1957	do
11	292	7,200	21.1	SE	310	1945	do
91	293	6,800	18.6	SW	400	1957	do
92	920	9,500	15.4	S	578	1957	do
94	1,520	13,700	15.9	SW	1404	1957	do
95	2,570	18,700	16.9	SW	1590	1957	do
97	4,580	29,500	17.2	SW	3345	1957	do
169	29.0	1,350	15.7	SW	75.8	1957	do
172	43.6	2,000	22.8	S	116	1957	Reforested
177	75.6	2,750	15.7	S	240	1957	Mixed cover under conser-vation practice
183	74.2	3,200	14.8	S	193	1946	Mixed cover under prevail-ing cover
192	7.59	720	15.8	NE	35.2	1946	Rotation crop
196	303	4,600	14.0	SE	1136	1957	Mixed cover under prevail-ing practice

Land Use and Treatment

The land treatments studied were those for several levels of crop and timber production, namely:

1. Average crop production and average soil stability (prevailing practice).

2. High crop production and considerable soil stability (improved practice).

3. Farm woodlot management and complete soil stability (reforested).

These levels of land management were imposed during the 1938-1940 period on each of the four mixed-cover watersheds. Watershed 196, 303 acres in area, was maintained essentially unchanged in management level (prevailing practice). Initially two-thirds of watershed 172, 43.6 acres, was in very poor pasture and idle land with the remaining area in hardwoods. It was completely reforested in the Spring of 1938 and 1939 and permitted to develop to date. Harrold, et al. (1962) reported that reforestation was successful; a one hundred percent forest cover was established and there has been no serious disease, insect damage, or fires during the study period. Watersheds 169, 29 acres, and 177, 75.6 acres, were converted from prevailing practice to improved land management. A detailed description of the improved and prevailing watershed treatments from 1947 to 1967 is shown in Table 2.

Analysis of the Hydrologic Data

Test for Precipitation Normalcy. Before studying the influence of land use and treatment, a check was made of whether the climate during the test period was representative of the long term climate of the area. If the test period was excessively wet or dry, it would limit the conclusions that could be inferred from the data.

The "U test" as developed by Mann and Whitney (1947) was used on the 58-year record (1909-66) of the city of Coshocton rain gage. The test period, 1938-66, was found to be entirely representative of the long-term normal, 1909-37, for both growing and dormant seasons as well as on an annual basis. Since the city of Coshocton record was highly correlated with precipitation on the experimental watersheds, precipitation on the treated watershed should also be entirely representative of the long-term climate of the area.

Annual and Seasonal Streamflow. In analyzing streamflow change with time, any variability not related to the imposed land practices should be removed. Seasonal climatic variations introduce sizable variations in streamflow. Statistical techniques used to remove the influence of climatic-induced variability included double-mass analyses, multiple regression using streamflow data from an untreated watershed (No. 196) as an index of climate, and multiple regression utilizing measurable climatic parameters. Results of the regression analyses using the index watershed are presented here. Any differences in results from the three analytical methods are noted.

A multiple regression with the index watershed involved first fitting an equation of the form:

Table 2. Description of Watershed Treatment, 1947-67[1]
(Adopted from Harrold et al. (1962)

Land Use	Watersheds and management level	
	196, Prevailing	169 and 177, Improved
Tillage	Across slope	Contour.
Planting Method	Entire field	Entire field or 2-to-3-acre fields; alternating strips of meadow and row crop or grain on 7.5-acre areas.
Fertilization per acre:		
Corn	Lime to pH 5.4 Manure 6 tons 2-12-6-100 pounds in the row.	Lime to pH 6.8 Manure 6 tons. 3-12-12-300 pounds in the row.
Wheat	2-12-6-125-pounds	3-12-12-300 pounds Manure topdressing 4 tons.
Meadow	None	0-20-20-200 pounds on first-year meadow.
Seeding rate per acre:		
Wheat	2 bushels	2 bushels.
Meadow in wheat	Timothy-3 pounds	Timothy-3 pounds.
Meadown, spring	Red clover-6 pounds Alsike-3 pounds Timothy-3 pounds	Alfalfa-6 pounds. Red clover- 4 pounds. Timothy-3 pounds.
Tillage operations	Plow late in April Disk twice Harrow Plant about May 10 Cultivate twice corn picked last of Sept. Stover disked into ground surface. Wheat drilled with fertilizer early in Oct. Grass and legumes broadcast late March Wheat combined by mid-July. Straw cut, raked, baled and removed by end July.	Plow late in April. Disk twice. Harrow. Plant about May 10. Cultivate twice Corn picked last of Sept. Stover disked into ground surface. Wheat drilled with fertilizer early in Oct. Grass and legumes broadcast late March. Wheat combined by mid-July. Straw cut, raked, baled and removed by end July.
Meadow cuttings per	Two (May-June and July-Aug.)	Two (May-June and July-Aug).

[1] From 1937-46, prevailing called for 75 pounds of 2-12-6 on corn and 125 pounds of 2-12-6 on wheat; improved called for 200 pounds of 2-12-6 on corn, 300 pounds of 2-12-6 on wheat, and 100 pounds of 0-20-0 on second-year meadow.

$$Q_{172} = A + B\,(Q_{196}) + C\,(t)$$

to the annual streamflow data. In this equation the dependent variable, Q_{172}, is the runoff from the treated watershed, Q_{196} is the runoff from the climatic index watershed, t is the elapsed time in years from the midpoint of the record, and A, B, and C are coefficients.

Climatic variations (as indexed by the flow from watershed 196) are then removed from the observed flow on the treated watershed 172 by the equation:

$$Q'_{172} = Q_{172} - B\,(Q_{196} - \bar{Q}_{196})$$

where Q' is the adjusted runoff from the treated watershed, and the bar over the last term indicates the mean value for the period of record. This equation adjusts the flow on watershed 172 in each year to what it would have been had the climate been exactly normal.

The final step involves fitting a regression line through the plotting of Q'_{172} values with time. Table 3 presents the results of the analyses on the three teated watersheds. This method, used by Brakensiek and Amerman (1960) is illustrated with the aid of Figure 4 which traces the analysis of annual runoff data from the reforested watershed.

The relationship between climatic index (water year streamflow on the base Watershed 196) versus time is shown in the top graph of Figure 4. The considerable scatter of these data reflect year-to-year climatic variation. The trend for the index to decrease with time, 0.16 inch per year, is significant at the 10 percent level and is probably a reflection of the gradual increase in the level of agricultural technology plus a minor long-term climatic trend during the 27 years.

The middle graph of Figure 4 shows the annual runoff from the reforested watershed 172 plotted against time. A linear regression shows a more pronounced trend for streamflow to decrease with time, the rate being 0.29 inch per year, which is significant at the 1 percent level. This trend has resulted in part from the "natural" trend shown in the top graph of Figure 4. Thus, to ascertain the effect of land use and treatment on streamflow, the "natural" trend was removed from the streamflow values of the reforested watershed by multiple-regression analysis.

Finally, a curvilinear regression of the adjusted watershed 172 streamflow on time is performed as shown in the bottom graph of Figure 4. Much of the scatter present in the middle graph has been removed by the above analysis. The curve in the lower graph of Figure 4 is a reasonable indication of the effects of land use and treatment on the annual streamflow from the reforested watershed 172.

A curvilinear regression was selected for the bottom plotting of Figure 4 because it seems logical that the reduction in streamflow resulting from an improvement in the level of land use and treatment would gradually diminish with time and eventually disappear. Thus, a new equilibrium in seasonal streamflow rate would be reached. Several forms of logarithmic equations were tried in this regression, with moderate success, but the reciprocal-of-time type was chosen to estimate the adjusted streamflow. Its form is:

$$Q'_{172} = A + B/T'$$

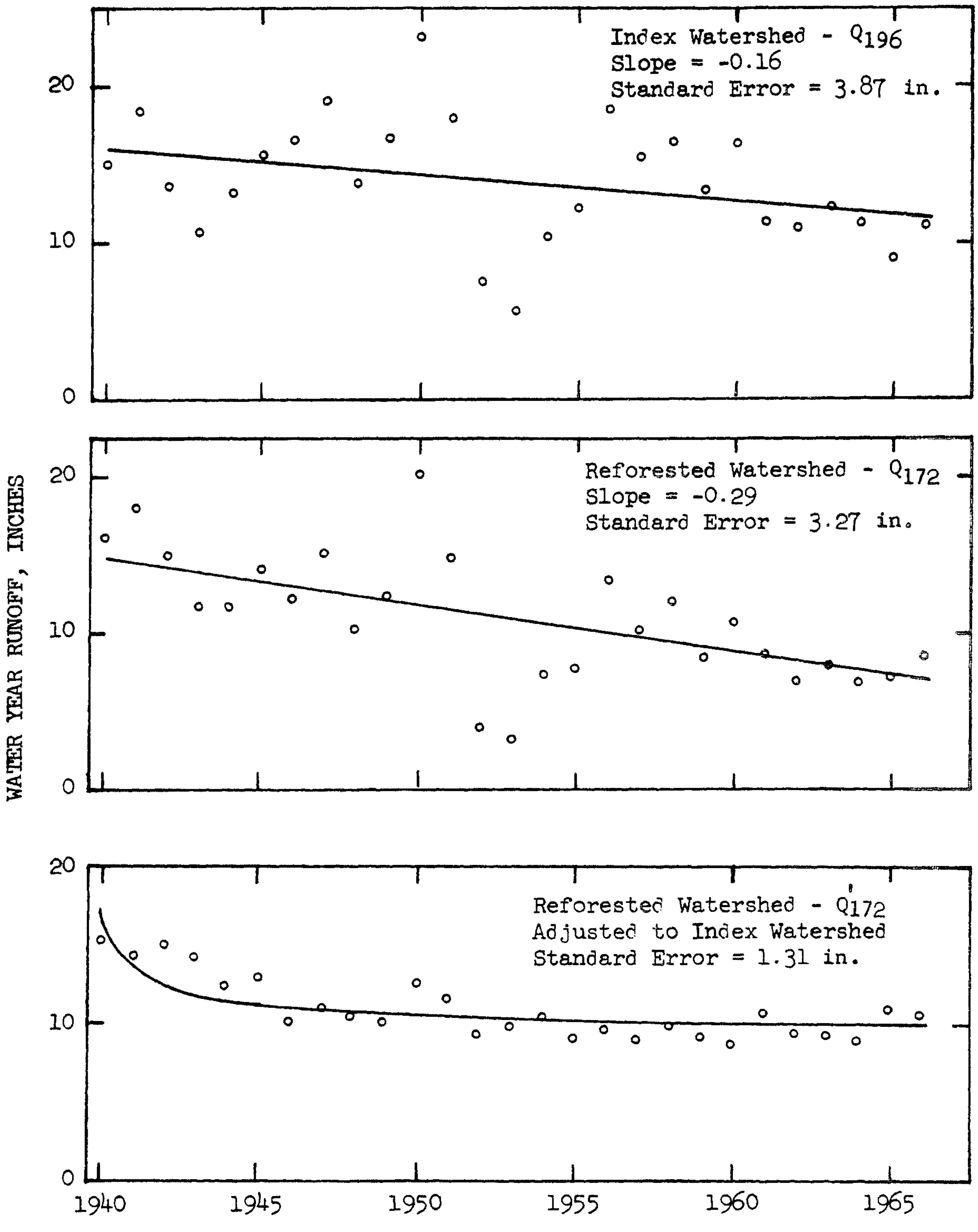

Figure 4. Graph of Analytical Method Utilizing Multiple Regression with Index Watershed.

Table 3. Reduction in Streamflow for the Period 1940 Through 1966 on the Study Watersheds

Watershed No.	Acres	Treatment	Water Year: 1940 flow in.	Water Year: Reduction by 1966, in.	Growing Season: 1940 flow, in.	Growing Season: Reduction by 1966, in.	Dormant Season: 1940 flow in.	Dormant Season: Reduction by 1966, in.
172	43.6	Reforested	17.30	7.19*	5.31	2.78*	12.04	4.46*
169	29.0	Improved	7.83	1.91**	2.88	1.42*	5.12	.67
177	75.6	Improved	8.95	1.49**	2.61	.97*	6.16	.31

*Statistically significant at the 1 percent level.
**Statistically significant at the 5 percent level.

where Q'_{172} is the estimated adjusted flow on watershed 172. A is the constant representing the new equilibrium rate, B is a regression coefficient, and T' is the lapsed time in years since the study began in 1939. The standard error of estimate has been reduced from 3.27 in. in the middle graph to 1.31 in the lower graph.

Table 3 shows that streamflow was reduced significantly during the growing season and during the entire water year on each of the treated watersheds. During the dormant season, the small flow reductions on the improved mixed-cover watersheds were not significant. The 41-1/2 percent reduction in streamflow for the reforested watershed was the highest response of the land uses studied.

Reduction values in the table are computed by subtracting the ordinate of the curve at 1966 in the lower graph of Figure 4 from the ordinate at 1940. For example, the curve value at 1966 equals 10.11 in., while for 1940 it is 17.30 in. The 7.19-in. difference is the reduction in annual runoff for the reforested watershed for the study period. Because of the curvilinear fit of the data, the figures in Table 3 for the growing and dormant season do not add exactly to the water-year values.

Results of the double-mass analyses and of multiple regression using climatic parameters are in general agreement with those derived from multiple regression with an index watershed (Table 3). All analyses indicated streamflow reductions on all watersheds in all periods, but the index watershed method was more sensitive. Significance of the findings from the current study is generally higher than in the original analyses performed by Harrold, et al. (1962). The bottom graph of Figure 4 indicates that the reduction in streamflow is gradually diminishing in time and should eventually disappear. This is in direct contrast to the findings in the earlier reports that the trend from 1940 to 1957 was linear with no evidence that a new lower equilibrium streamflow had been reached. Regression analyses were used to determine whether the trend toward decreasing flow with time continues or has ceased.

The full effect of reforestation on the hydrologic behavior of the watershed has been achieved in a statistical sense. Figure 5 shows the adjusted data from the bottom graph of Figure 4. A linear regression line fitted through the first 10 years of annual data has a slope of -0.65, significant at the 0.1 percent level; however, a regression line fitted through the last 10 data points has a slope of 0.14, not significant. Annual streamflow reductions resulting from reforestation, while significant in the initial period, have become an insignificant amount.

Table 4 gives the coefficients indicating the slope of the regression lines in the first and last 10-year periods on all three treated watersheds for the various seasons. Changes in streamflow resulting from reforestation are not apparent in the 1957-66 period in either the growing or dormant season or for the entire water year. Trends in streamflow on the improved mixed-cover watersheds are in the same direction as on the reforested area, with the 1940-49 slopes all being negative and the 1947-66 slopes all being positive. The probabilities are such that the interpretation for improved cropped areas are not as clear cut as for the reforested watershed.

Table 4. Linear Regression Coefficients of Adjusted Streamflow on Time Using The First and Last 10 Years of Data

Watershed No.	Acres	Treatment	Water Year		Growing Season		Dormant Season	
			1940-49	1957-66	1940-49	1957-66	1940-49	1957-66
			in.	in.	in.	in.	in.	in.
172	43.6	Reforested	-0.65*	0.14	-0.27*	0.04	-0.40*	0.12
169	29.0	Improved	-0.15	0.14*	-0.12**	0.06	-0.07	0.08
177	75.6	Improved	-0.23**	0.10	-0.12**	0.00	-0.13	0.15*

*Statistically significant at the 1 percent level.
**Statistically significant at the 5 percent level.

Flow Regions and Peak Discharges. Table 5 shows how the changes in streamflow due to land use and treatment were associated with periods of high, intermediate, and low flows. Reforestation significantly reduced high-flow volumes in the dormant season and low flows in both the growing and dormant seasons. In general, changes in flows from the two improved watersheds were smaller and were not consistent.

Even with the additional 9 years of data, there is still no indication that reforestation has affected the major peak rates of flow. These peaks were produced by the storms of extreme intensity and volume and were reexamined by the method used by Harrold, et al. (1962). Since reforestation is more likely to produce a change in peak rates than is improved cropland, the analysis was not extended to cropland watersheds.

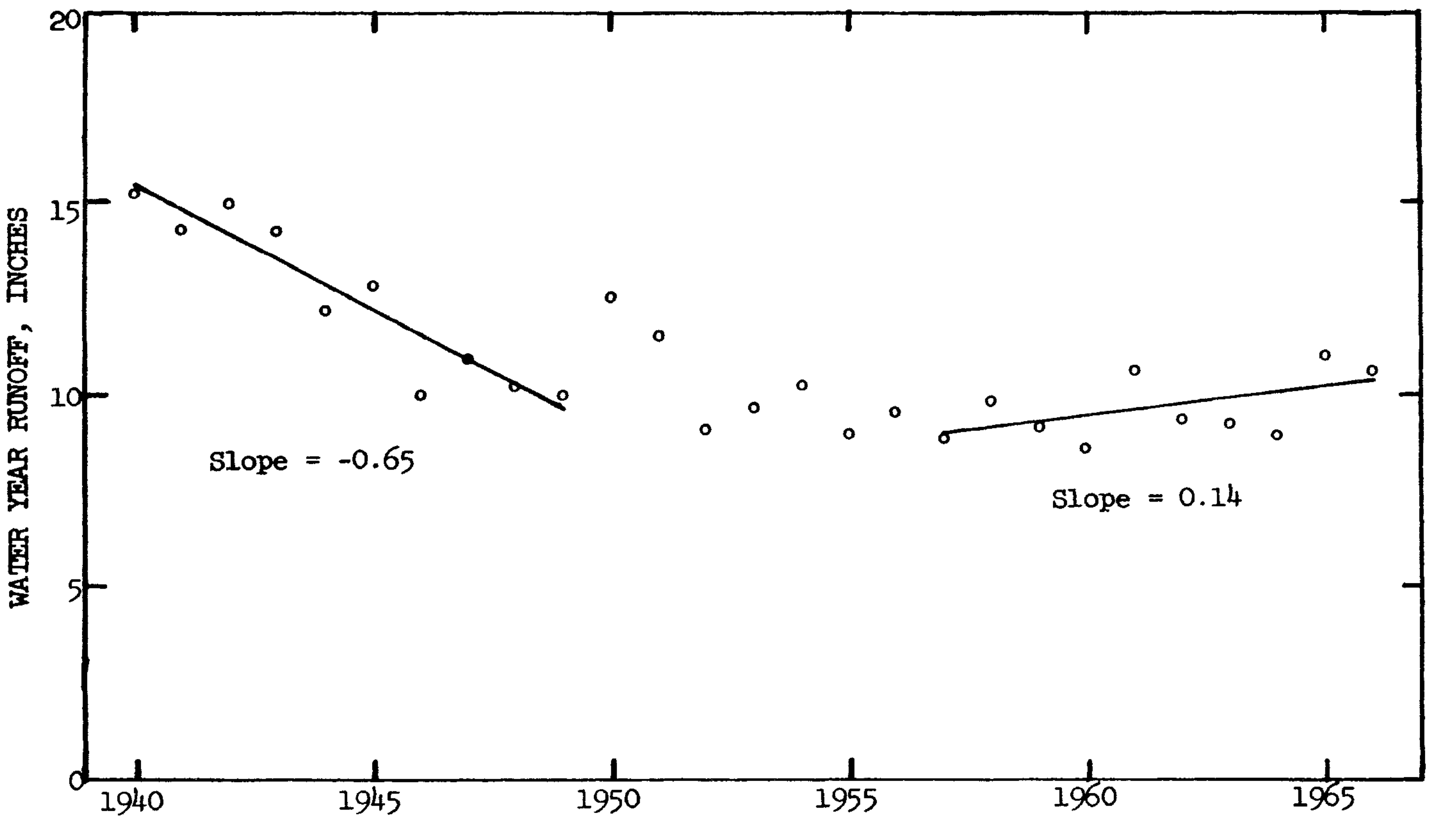

Figure 5. Regressions Using First Ten Years and Last Ten Years of Reforested Watershed Streamflow Adjusted for Climate Index.

Table 5. Average Seasonal Runoff in Different Flow Regimes and Changes Due to Land Use and Treatment (1940-1966)

Watershed No.	Acres	Treatment	Growing Season Average, in.	Growing Season Change per Year, in.	Dormant Season Average in.	Dormant Season Change per Year, in.
			High Flow: $Q \geq 0.1$ in. per day			
172	43.6	Reforested	1.39	-0.007	4.56	-0.054**
169	29.0	Improved	1.11	-0.023**	3.12	-0.036**
177	75.6	Improved	1.09	-0.011	3.65	-0.009
			Intermediate Flow: $0.1 > Q > 0.05$ in. per day			
172	43.6	Reforested	0.53	0.001	1.81	-0.018*
169	29.0	Improved	0.27	-0.001	0.85	-0.005
177	75.6	Improved	0.32	0.005*	1.30	-0.002
			Low Flow: $Q \leq 0.05$ in. per day			
172	43.6	Reforested	0.92	-0.026**	1.73	-0.041**
169	29.0	Improved	0.25	0.002	0.55	-0.007
177	75.6	Improved	0.31	0.003	0.93	0.010

*Statistically significant at the 5 percent level.
**Statistically significant at the 1 percent level.

Percolation Investigation. Data from the monolith lysimeters, described in detail by Harrold and Dreibelbis (1958) were used to assess the influence of improved practice on percolation behavior. Over the 29-year period two of the lysimeters were maintained in permanent grass, one in poverty grass and the other in fertilized bluegrass followed by deep-rooted legume cover. Twenty-six years of data were available on the four rotation-cropped lysimeters. Two of these were farmed in prevailing and two in improved practice as described in Table 2.

The sign test described by Dixon and Massey (1951) showed that improved practice significantly decreased percolation amounts in both growing and dormant seasons under cropland and in the growing season under meadow.

Ground-Water Table Behavior. A regression analysis was run on the water levels in a groundwater well located in the reforested watershed. Levels on November 1 were tabulated for each year as an index of conditions at the end of the growing season. Over the 29 years of record, the water surface elevation decreased at an average rate of 0.70 in. per year. This indicates an increase in consumptive use of soil water by the relatively deep-rooted trees compared with the initial shallow-rooted cover. The May 1 water level which indexed conditions at the end of the dormant season recharge period showed no trend with time, indicating that the soil water deficit incurred in the growing season was being completely recharged during the dormant season.

Comments and Interpretations

The current study confirms the general performance findings reported by Harrold, et al. (1962). More importantly, streamflow performance in recent years shows that the effects of land use and treatment changes initiated in the 1936-40 period have essentially become complete. Thus, the watersheds discussed in this report can be used in an updated experimental program.

The analyses tend to confirm a hypothesis that improved land use and treatment increased infiltration potential. The data of Table 3 indicate substantial reductions in growing-season streamflow on all watersheds. Summer runoff is primarily surface runoff, so the influence of increased infiltration should be greatest during this season. Table 5 also shows reductions in the high-flow regimes on all watersheds in the growing season, although the statistical significance is not well established.

The data do not completely confirm a hypothesis of reduced percolation potential with improved land-use practices. More vigorous growth and deeper rooting systems resulting from improved treatment and reforestation dry out the soil to deeper depths by the end of the growing season. A larger reservoir in the soil must be filled before excess water can percolate beyond the root zone and recharge the water tables. Reduction in dormant-season flows (Table 3) and the decline in the November 1 level of the groundwater well suggest a decreased percolation potential. However, if the hypothesis was true, the low flows should be reduced during the dormant season. This was not observed (Table 5). Geological conditions at the two improved watersheds are such that part of the base flow may be escaping measurement; however, all the reforested watershed runoff should be flowing through the gage.

The twin hypothesis of increased infiltration and decreased percolation potentials means that reforestation should have increased evapotranspiration. Mustonen and McGuinness (1968) investigated this possibility and found a pronounced increase in evapotranspiration on the reforested watershed during the 1939 to 1949 period, after which time the rate was essentially constant. Their finding fits in well with the pattern of streamflow shown on the bottom graph of Figure 4. They also made a water-budget study on watershed 196, the index watershed in the current study, and found no time trend in evapotranspiration.

Some additional study might be warranted on peak rates. The analytical method used was a modified index watershed approach. Perhaps a method which takes into account more of the measurable climatic parameters might prove more sensitive. Some additional geologic information about the study watersheds might help explain the inconsistent behavior in the low flow regine. If the hydrographs could be separated into surface, interflow, and base-flow components, a study of the effects of land use and treatment on each flow type might be informative. More details about this study are contained in the Master of Science thesis by Simmons (1968).

Summary

Thirty years of runoff data from agricultural watersheds at the North Appalachian Experimental Watershed were analyzed to determine the effects of

land use on streamflow. Reforestation and improved cropping reduced annual and seasonal streamflow. High flows were reduced in both seasons, but the treatment effects on low flows were not consistent. A decrease in percolation potential was indicated by the declining trend of the November 1 groundwater level. The time trend of flow changed from strongly negative in the first 10 years to insignificant in the last 10 years of record, indicating that the major effects of land use and treatment on streamflow have been reached. Hydrologically, the treated watersheds have stabilized in their new flow regimes.

INSTRUMENTATION OF A STRIP MINE-STUDY AREA FOR HYDROLOGIC INVESTIGATIONS

Introduction

Strip-mining is an important economic activity in the United States. According to Udall (1967) approximately 800,000 acres of land were strip-mined by January 1, 1965. As the demand for generated power increases, secondary grades of coal become more important to the power companies; this has caused an increase in mining operations.

This type of activity brings with it several problems. Toxic effluent, increased sediment materials, destruction of possible farmland and wildlife habitat, landslides, and poor aesthetics are some of the problems that might accompany careless strip-mining operations. In order to study the effects of strip-mining on watershed hydrology, an instrumentation network was designed and installed in a recently strip-mined 20-acre watershed, No. 19, in the Little Mill Creek basin at Coshocton, Ohio. This network was designed to monitor rainfall, runoff, sediment, evaporation, groundwater levels, mass movement of spoil material, and seepage rates from the strip-mine pool.

Instrumentation

Two rain gages were installed to measure the rainfall both outside and inside the mining pit. A 3'-H flume for high flows and a 0.6'-HS flume for low flows were installed to measure the runoff from watershed No. 19. The Coshocton wheel sediment sampler was never made operational. It was removed.* The water level in the strip-pool was measured by an FW-1 continuous water stage recorder and the pool evaporation was monitored by a floating evaporation pan. A network of piezometric tubes was installed in the spoil material to aid in determining the groundwater profiles. The tubes are 0.5 inch inside diameter and are made of steel 3/16-inch thick. The tips were perforated for the first 3 feet at 1" intervals. Control points were established and an initial survey was made to determine the position of the spoil bank. A periodic re-survey will give an indication of bank movements. The details of this study were reported by Wicks (1968).

Analysis of Initial Data

Although several years of data are necessary in making adequate predictions regarding watershed response, some data yield immediate suggestions toward a reliable prognosis.

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*Flows were not high enough to produce sufficient samples.

Inspection of pool stage data and evaporation pan data indicates that a net seepage from the strip-pool exists on days of no recorded precipitation. The piezometric tube data verifies the location of this seepage. Groundwater levels during the Spring tend to show outflow occurring from all sides of the pool. This would result in a seepage loss to the adjacent watershed and should be accounted for.

Evaporation pan data were compared with those collected at the North Appalachian Experimental Watershed's Class A pan to see if correspondence were evident. Figure 6 shows much scatter is prevalent, using daily values, rather than 3-day or weekly averages. Data from rainless days were compared so that differences in rain catch in nearby gages and that caught by the pan would not affect the comparison. The regression equation obtained from the analysis is: Floating = 0.8804 Class A - 0.0046, with input data being evaporation in inches per day measured from 0800 to 0800 E.S.T. From the regression equation above, evaporation from the floating pan was less than that from the Class A pan but data are too scarce to make any reliable statements.

The raingage network employed at the study area was analyzed for differences in catch. It was found that slight differences did exist, so a comparison was made with nearby raingages No. 54 and No. 103, of the North Appalachian Experimental Watershed, both being about 3200 feet west and east, respectively, from the flume site of Watershed 19. The average of the two gages at Watershed 19 was compared with the average from gages 54 and 103. The regression equation is: $Y = 0.9203X + 0.0123$, where Y is the average precipitation from the strip pool gages, in inches per day, and X is the average of 54 and 103 raingage data in inches per day. Figure 7 illustrates this comparison which yielded a correlation coefficient of 0.999. These statistics show that good precipitation data for Watershed 19 may be obtained by computing the average catch from gages 54 and 103.

Runoff data for 23 days were analyzed and are shown in Table 6. Base flow measurements were steady at about 0.002 cfs.

A chemical analysis of the waters taken at various locations within Watershed 19 was made. There is a definite trend of increasing pH values in the strip pool from an average of 4.4 on June 28 to an average of 5.9 on August 21. A single value of 6.18 was noted on October 3, 1968. This may be due in part to the recharging of the pool from direct rainwater and not groundwater flow from the spoil banks. The results of the chemical analysis are given in Table 7.

Future Study of Watershed 19

Since time is needed before adequate prediction can be made regarding watershed response to strip-mining operations, the study of Watershed 19 should continue along the following lines:

1. Bank movements should be monitored by surveying periodically, preferably after the spring thaw or after any high-intensity storms of long duration. Survey control points and the piezometer tubes should be checked annually for settlement.

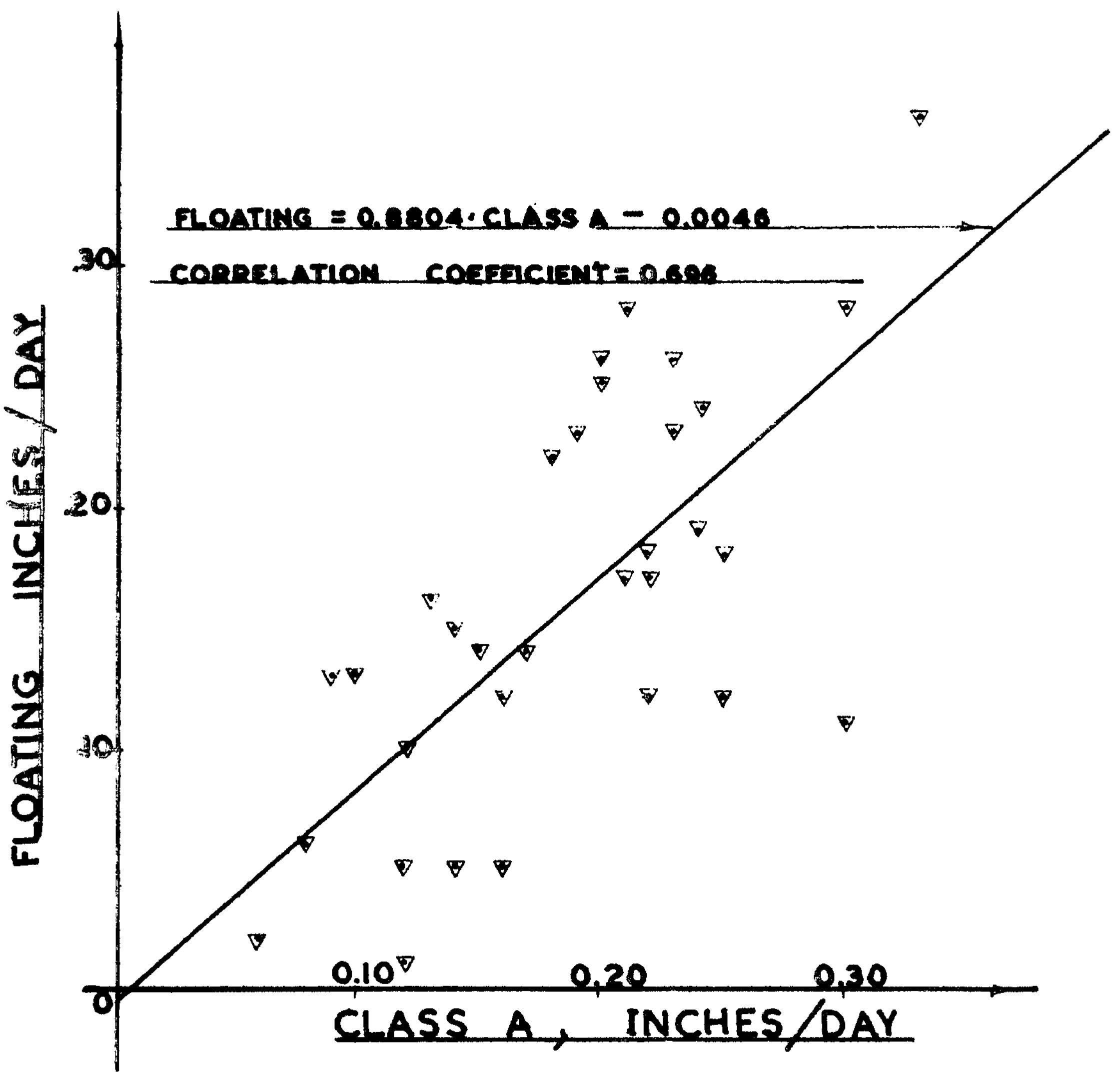

Figure 6. Correlation of Floating Pan Data with Class A Pan Data.

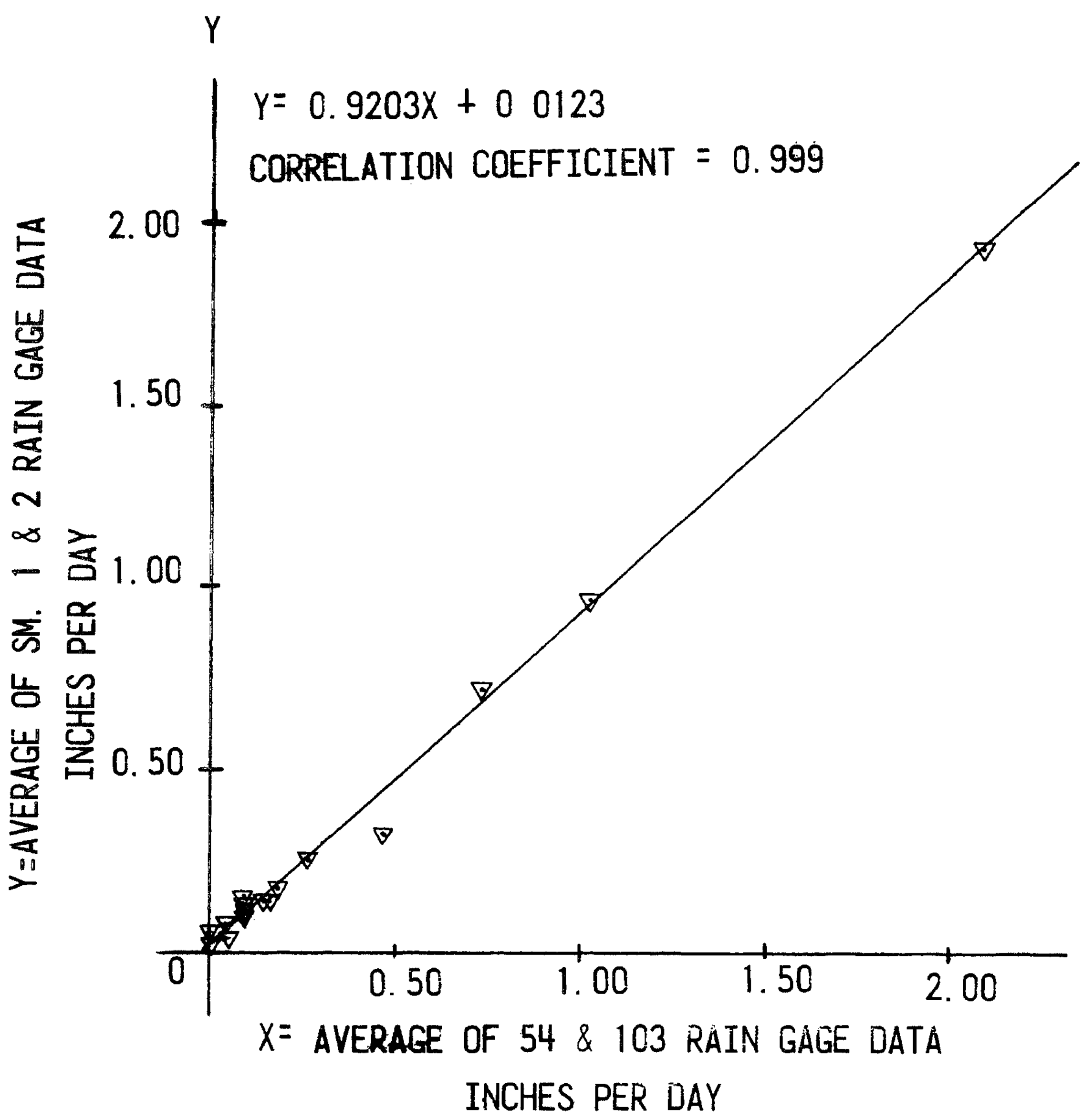

Figure 7. Correlation of Wsd. 19 Rain Gage Data with Gage Nos. 54 and 103.

Table 6. Runoff Tabulations

DAY	TIME MILITARY	STAGE FT.	RATE C.F.S.	RATE INCHES/HOUR	ACCUMULATIVE INCHES	COMMENT
9-9-68	2300	.063	.00213	.00009	0.0021	CFS=IPH/.04385
9	2400	.075	.00297	.00013	0.0022	Rained 9-9-68
10	0200	.065	.00226	.00010	0.0003	
10	1000	.063	.00213	.00009	0.0011	Rained 9-10-68
10	1100	.140	.0100	.00044	0.0014	
10	1120	.235	.0290	.00013	0.0015	
10	1200	.100	.00517	.00023	0.0016	
10	1300	.075	.00297	.00013	0.0018	
10	1800	.065	.00226	.00010	0.0024	
10	2400	.065	.00226	.00010	0.0030	
11	0200	.065	.00226	.00010	0.0002	
11	0300	.068	.00246	.00011	0.0003	Rained 9-11-68
11	0330	.090	.00421	.00019	0.0004	
11	0345	.070	.00259	.00011	0.0004	
11	0400	.080	.00335	.00015	0.0004	
11	0415	.098	.00498	.00022	0.0004	
11	0500	.080	.00335	.00015	0.0005	
11	0545	.099	.00507	.00022	0.0006	
11	0700	.075	.00297	.00013	0.0008	
11	0800	.070	.00259	.00011	0.0009	
11	1200	.068	.00246	.00011	0.0013	
11	1330	.096	.00479	.00021	0.0015	
11	1600	.068	.00246	.00011	0.0019	
11	2400	.065	.00226	.00010	0.0027	
12	2400	.060	.00193	.00008	0.0022	
13	2400	.065	.00226	.00010	0.0022	
14	2400	.060	.00193	.00008	0.0022	
15	2400	.060	.00193	.00008	0.0019	
16	2400	.060	.00193	.00008	0.0019	
17	2400	.060	.00193	.00008	0.0019	
18	1900	.060	.00193	.00008	0.0015	Rained 9-18-68
18	2015	.085	.00364	.00016	0.0017	
18	2100	.065	.00226	.00010	0.0018	
18	2200	.083	.00347	.00015	0.0019	
18	2400	.060	.00193	.00008	0.0021	
19	0600	.060	.00193	.00008	0.0005	Rained 9-19-68
19	0800	.090	.00421	.00019	0.0008	
19	1200	.065	.00226	.00010	0.0014	

Table 6. (Continued)

DAY	TIME MILITARY	STAGE FT.	RATE C.F.S.	RATE INCHES/HOUR	ACCUMULATIVE INCHES	COMMENT
19	1500	.060	.00193	.00008	0.0017	
19	1600	.100	.00517	.00023	0.0019	
19	1800	.065	.00226	.00010	0.0022	
19	2400	.062	.00200	.00009	0.0028	
20	2400	.060	.00193	.00008	0.0020	
21	2400	.060	.00193	.00008	0.0019	
22	2400	.060	.00193	.00008	0.0019	
23	0700	.060	.00193	.00008	0.0006	Rained 9-23-68
23	0715	.500	.152	.00666	0.0014	
23	0720	.36***	.329	.01441	0.0023	***=Gage ht.
23	0730	.500	.152	.00666	0.0041	of 3'-H Flume
23	0800	.190	.0186	.00082	0.0060	
23	0900	.100	.00517	.00023	0.0065	
23	1200	.065	.00226	.00010	0.0070	
23	2400	.065	.00226	.00010	0.0082	
24	2400	.065	.00226	.00010	0.0024	
25	2400	.060	.00193	.00008	0.0022	
26	2400	.055	.00166	.00007	0.0018	
27	2400	.052	.00149	.00007	0.0017	
28	2400	.050	.00138	.00006	0.0016	
29	2400	.052	.00149	.00007	0.0016	
30	2400	.050	.00138	.00006	0.0016	
10-1-68	2400	.045	.00114	.00005	0.0013	

Table 7. Results, Chemical Analysis of Water-Watershed 19.

CHEMICAL PROPERTY	DATE	POOL; EAST LEG	POOL; MIDDLE	POOL; SOUTH LEG	STREAM EFFLUENT (VALLEY)	GROUND WATER (VALLEY)	PUDDLE; ABOVE POOL
pH	6-28-68	4.40	5.20	3.50			
	7-31-68	5.45		4.35			
	8- 2-68	5.40		4.40			
	8	5.90		4.65	6.20		
	15	6.10		4.45	6.10	5.55	
	16	6.20		4.60			
	21	6.30	6.40	4.95			
	10- 3-68		6.18		5.55	6.16	3.70
IRON (ppm)	8-15-68	0.12		0.53	2.70	0.03	
	10- 3-68		0.18		1.21	5.00	1.14
TOTAL HARDNESS (ppm as $CaCO_3$)	8-15-68	1760		1900	950	960	
	10- 3-68		1250Ca 650Mg 1900TH		900Ca 440Mg 1340TH	725Ca 375Mg 1100TH	250Ca 75Mg 325TH
TOTAL ALKALINITY; (ppm as $CaCO_3$)	10- 3-68		12		18	90	0.00
MANGANESE (ppm)	10- 3-68		13?		10.0	14.8	1.8
SULFATE (ppm)	10- 3-68		1600		1200	950	150
ALUMINUM (ppm)	10- 3-68		0.30		1.5?	0.52	2.5?
SPECIFIC CONDUCTANCE	10- 3-68		2825		2000	1660	720

Note: Chemical analysis of the water samples was conducted by Mr. Brad Caswell, graduate student majoring in Geology at the Ohio State University. Mr. Caswell used a Hach portable water testing laboratory in making the analysis.

2. Groundwater fluctuations in the spoil banks should be monitored at least once monthly and preferably more often during the Spring.

3. It is essential for seepage investigations that pool elevation be checked at the same time as the piezometer tubes so that groundwater elevations may be connected with the pool.

4. Water samples of stream effluent should be collected once weekly when charts are being changed at the flume installation.

5. Sediment samples should be collected after each storm which yields runoff exceeding the capacity of the 0.6'-HS flume.

APPLICABILITY OF RUNOFF FORMULAS TO COSHOCTON WATERSHED

Introduction

Drainage structure design requires the best possible estimate of peak runoff rate at the proposed site. Unfortunately, adequate streamflow records for small watersheds are limited or nonexistent. Nevertheless some satisfactory method must be employed to estimate the required peak rate for these cases, and as a result many peak rate formulas have been developed and are in use.

Around 15 percent of highway costs is spent on the construction and maintenance of minor drainage structures at small stream crossings. It is evident that uneconomical design resulting from overestimation of peak flows will considerably increase the construction costs. Also costly is underdesign which may cause a high degree of damage. Because of the great variation in the peak runoff rate determined by the various available methods a study was designed to investigate the applicability and performance of four, more prominent of the many peak runoff prediction methods to the Ohio area. The North Appalachian Experimental Watershed at Coshocton was used for the study. The four methods used in the investigation are Rational, Cook, BPR, and Chow method.

The Runoff Formulas

The Rational Formula. The rational formula is

$$Q = CIA$$

in which Q is peak runoff in cfs, C is runoff coefficient depending on basic characteristics, I is rainfall intensity in inches per hour for a duration equal to time of concentration[1] of the basin, and A is drainage area in acres. The assumptions inherent in this formula were interpreted by Chow (1964) as follows:

1. The rate of runoff resulting from any rainfall intensity is a maximum when this rainfall intensity lasts as long or longer

[1] Time of concentration is the time required for the surface runoff from the remotest part of the drainage basin to reach the point being considered.

than the time of concentration.

2. The maximum runoff resulting from a rainfall intensity, with a duration equal to or greater than the time of concentration, is a simple fraction of such rainfall intensity; that is, it assumes a linear relation between Q and I, and Q = 0 when I = 0.

3. The frequency of peak discharge is the same as that of the rainfall intensity for the given time of concentration.

4. The relationship between peak discharges in inches over the basin and size of drainage area is analogous to the relationship between the intensity of rainfall and storm duration.

5. The coefficient of runoff is a constant value for a given watershed, regardless of storm size and frequency.

Even though some of these assumptions cannot be satisfied under field application, its simplicity has made the rational formula popular.

The Cook Method. According to Hamilton and Jepson (1940) this method was originally eveloped by H. L. Cook of the Soil Conservation Service in 1938. The working curves are based on the results of runoff studies, representative formulas of flood flow, and runoff coefficients. The procedure uses an empirical relationship between drainage area and peak flow with modifications for watershed characteristics such as relief, infiltration, vegetal cover, and surface storage. Incremental values, W, are assigned to reflect the extent of the watershed characteristics and tabulated in a manner such that a very systematic procedure obtains. Summation of "W" reflects the hydrologic condition of the watershed. A first estimate of peak flow at 50-year return period is obtained from the empirical relationship as stated above.

A correction has to be made to compensate for the great geographic variation in rainfall intensities. An isohyetal map is drawn so that the rainfall factor, R, that provides a reasonable geographic correction, could be read for any locality in the United States. In drawing such a map, Central Iowa is designated as the base location having the rainfall factor of "1". A final estimate of 50-year frequency peak flow, Q_{50}, is computed as the product of the rainfall factor and the first estimate.

The estimates of peak flow at the 10-year frequency, Q_{10}, and 25-year frequency, Q_{25}, require the application of frequency factor, F, which is governed by the average annual precipitation and the "W" value from infiltration and vegetal cover. A_{10} and Q_{25} are obtained by multiplication of Q_{50} with its corresponding frequency factor. The Cook Method is limited to watersheds less than 600 acres.

The BPR Method. Potter (1961) presented a procedure for practical application of the results of a research study of peak rates of runoff from small watersheds. His study was limited to watersheds with areas of 25 square miles or less, located east of the 105th meridian. The region was classified into four zones according to underlying rock formations. The watershed samples were divided into two groups, i.e., a group of 246 ungaged watersheds and a group of 96 gaged watersheds.

Part I of his investigation dealt with an analysis of the drainage characteristics of the ungaged watershed samples. Within a zone of homogeneous lithology, correlations were established between a topographic index T, a precipitation index P, and the watershed area A. The topographic index T is defined as the sum of the ratio of seven-tenths the length of the principal stream channel to the square root of its slope, plus the same ratio determined for the remaining three-tenths of its length. Channel lengths are measured in miles and slopes in feet per mile. The precipitation index P is defined as the amount of precipitation, measured in inches of rainfall, that might be expected to be equalled or exceeded during a 60-minute period on an average of once in 10 years.

He contended that errors in estimates of T, obtained from these correlations, could be explained by differences in drainage characteristics of the watershed. The drainage characteristics are expressed by the watershed's drainage density index D which is defined as the ratio of the summation of the length of all stream channels within a watershed to the watershed area $(\frac{\Sigma L}{A})$. Thus, the magnitude of the error in estimates of T can be used as an indication of the degree to which the drainage characteristics of a watershed differ from those of the watersheds on which the correlation was based.

The analysis in Part I was used in Part II, the study of gaged watershed samples, to divide the 96 gaged watersheds into two subgroups: Subgroup 1 watersheds with drainage characteristics similar to those on which the correlation was based and Subgroup 2 watersheds with drainage characteristics differed by varying degrees. Correlations were established, for subgroup 1 watersheds, between the peak runoff for an average return period of 10 years, Q_{10}, and the indexes T, P, and A. These correlations were used to obtain estimated values of Q_{10} for the subgroup 2 watersheds. He showed that the errors in these estimates bear a close relation to the corresponding errors in the estimates of T. This relation is used to obtain a correction coefficient C which can be applied to the estimate of Q_{10} when the estimate of T indicates a difference in drainage characteristics.

<u>The Chow Method</u>. Chow (1962) published a practical method for determining peak runoff from small drainage basins of less than 6000 acres.

This method computes peak runoff from a drainage basin as a product of the rainfall excess and the peak runoff of a unit hydrograph[1], or

$$Q = R_e P \tag{1}$$

in which Q is a peak runoff in cfs, R_e is rainfall excess in inches for a duration of t hour, and P is peak runoff of a unit hydrograph in cfs/in. for t hour of rainfall excess.

Considering a rate of rainfall excess equal to 1 in. per t hr. and the drainage area of A acres, the equilibrium runoff is equal to 1.008 A/t cfs.

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[1]A unit hydrograph is defined as the hydrograph of direct runoff (ground water excluded) from a given basin resulting from 1 in. of excess rainfall generated uniformly over the basin area at a uniform rate during a specified duration.

Using the concept of peak-reduction factor, Z, which is defined as the ratio of the unit hydrograph peak discharge P to the equilibrium runoff 1.008 A/t, or

$$Z = \frac{Pt}{1.008\ A} \tag{2}$$

Then, substituting equation (2) in equation (1)

$$Q = \frac{1.008\ R_eAZ}{t} \tag{3}$$

In equation (3), the factor 1.008 R_e/t is replaced by the product of two factors: X and Y. Consequently,

$$Q = AXYZ$$

where X is a runoff factor, expressed by

$$X = \frac{R_{eo}}{t}$$

where R_{eo} is the rainfall excess in inches at a given location, increased by 6.0 percent to allow for the effect of variable rainfall distribution in the duration of t hour, and Y is a climatic factor. Assuming $R_e/R_{eo} = R/R_o$ this climatic factor is

$$Y = \frac{1.008\ R}{R_o}$$

where R_o is the rainfall in inches at the base location in duration t hour, and R is the rainfall in inches at the location to be investigated in duration t hour.

If the base flow at the time of the peak runoff is Q_b, then the design peak runoff is

$$Q_d = Q + Q_b$$

Chow (1962) stated that "Although the procedure illustrated in this report was prepared for design conditions in Illinois, the concept of the method is universally applicable to other states provided adequate data in these states are available for similar analysis and development".

Computer programs were developed for the BPR and the Chow method which involve a considerable amount of computation. Aerial photographs (scale 1:12,000) were extensively used to obtain quantitative values for watershed characteristics such as soil type, watershed cover, infiltration, and surface storage. Photo-interpretation played a very important role in this study by providing a reliable information and saving a large amount of time which would otherwise be required for field survey. A procedural outline for applying each of the flood formulas is given by Sopak (1969).

Frequency Analysis

To obtain the most reasonable estimates of peak runoff rates at various frequencies, three more commonly used methods of flow-frequency analysis were applied to Coshocton watersheds. These are the log-Pearson Type III, Hazen, and Gumbel method. The development and procedure for applying these methods are described in several textbooks and have been summarized in a publication by Inter-Agency Committee on Water Resources (1966).

The best estimates of peak runoff rates at various frequencies are referred to as standard values. Since the precision of the individual method is still questionable the standard values were adopted as the arithmetic means of the results of the three flow-frequency analysis methods.

This study also provided an opportunity to judge which is the most precise flow-frequency analysis method among the log-Pearson Type III, Hazen, and Gumbel method. For this purpose the results of each method were compared to the corresponding standard values by computing the deviation using

$$D = \frac{Q_f - Q_s}{Q_s} \cdot 100$$

where D is the deviation from standard value in percent, Q_f is the computed value from the method of frequency analysis, and Q_s is the corresponding standard value. Figure 8 shows a plot of the average deviations of each method against return periods. From the figure it is observed that Gumbel method provides higher values at short-return periods (2, 5, and 10 years) and lower values at high-return periods (50, 100, and 200 years). The log-Pearson Type III consistently gives somewhat lower values than the Hazen method at every return period. The results from the three methods are almost the same at the 25-year return period.

Positive and negative deviations tend to neutralize each other which means that the fluctuations resulting from the differences between positive and negative deviations are completely ignored. This disadvantage was overcome by considering the average positive and negative deviations separately. As shown in Figure 9, the fluctuations of each method were represented by the departures of the average positive deviations from the corresponding average negative deviations. Figures 8 and 9 indicate that the method of Hazen is the most precise since the overall average deviations and the fluctuations are relatively small.

Evaluation of the Runoff Formulas

The evaluation of the relative performance of the four runoff prediction methods, the rational formula, the Cook, the BPR, and the Chow method, was restricted to only three frequencies which are usually considered for drainage structure design in small watersheds, namely, 10, 25 and 50 years. The departures from the standard value of the runoff rates obtained from the runoff prediction methods were computed from

$$D = \frac{Q_p - Q_s}{Q_s} \cdot 100$$

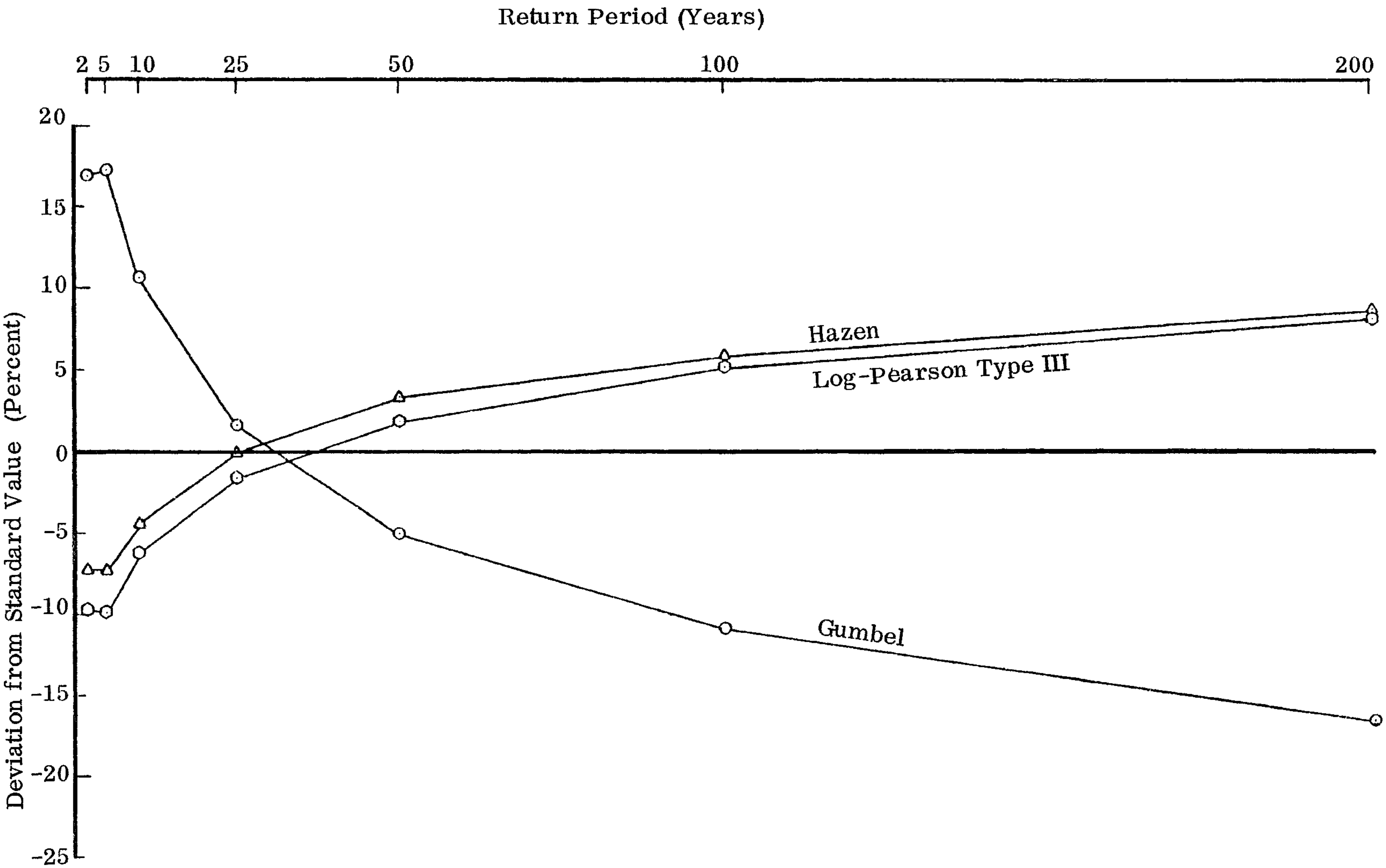

Figure 8. Average Deviations of Computed Discharges from Standard Values.

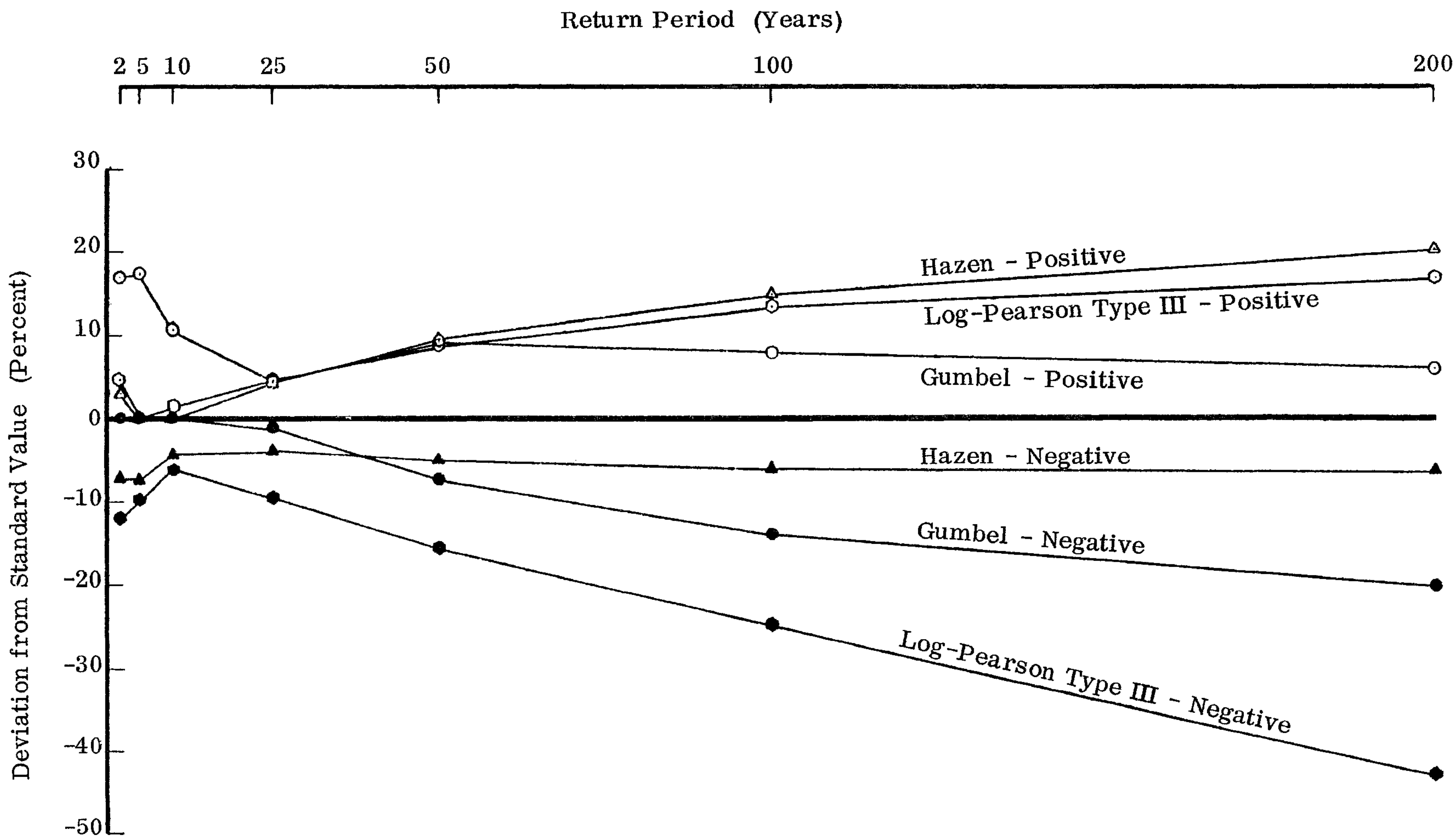

Figure 9. Average Positive and Negative Deviations of Computed Discharges from Standard Values.

where D is the deviation from standard value in percent, Q_p is the predicted runoff rate, and Q_s is the corresponding standard value.

As stated previously, the idea of the average deviations is insufficient to arrive at the conclusion concerning the relative precision of each method. To eliminate this problem, the knowledge of correlation index was introduced and was computed at 10, 25, and 50-year return periods as follows:

$$C = 1 - \sigma_p^2/\sigma_s^2$$

in which

$$\sigma_p^2 = \Sigma(Q_s - Q_p)^2/n$$

$$\sigma_s^2 = \Sigma(Q_s - \overline{Q}_s)^2/n$$

$$\overline{Q}_s = \Sigma Q_s/n$$

where C is correlation index and n is the number of standard values. The closer the correlation index is to 1 the better the performance.

The deviation from the standard value was plotted against the return period in Figure 10 and the correlation index was plotted against the return period in Figure 11. Figure 10 suggests the following:

1. The rational formula, the Cook, and the Chow method have a tendency to overestimate the peak runoff rates at every return period. The situation is reversed for the BPR method.

2. The predicted values get closer to the standard values at shorter return periods except for the rational formula which provides better estimates at higher return periods.

3. The rational formula produces the highest overestimates.

From Figure 11 it is obvious that the Chow method has the highest degree of correlation and the Cook method shows a severe lack of correlation. Based on the findings of this study, the conclusion is that the Chow method is the most precise and it is recommended for predicting peak runoff rates in small drainage basins in Ohio. The other three methods can be arranged in decreasing order of precision as: The BPR, the Cook, and the rational formula.

The experience of this study indicated that the application of the Chow method is rather laborious and requires a great deal of information. When data are limited, the BPR method should be applied since it gives second highest precision and requires much less amount of information. Since the range of uncertainty in the estimation of peak runoff rates is quite large and relatively high deviations from the standard values exist in every method, research in this field should be continued to assure truly satisfactory results.

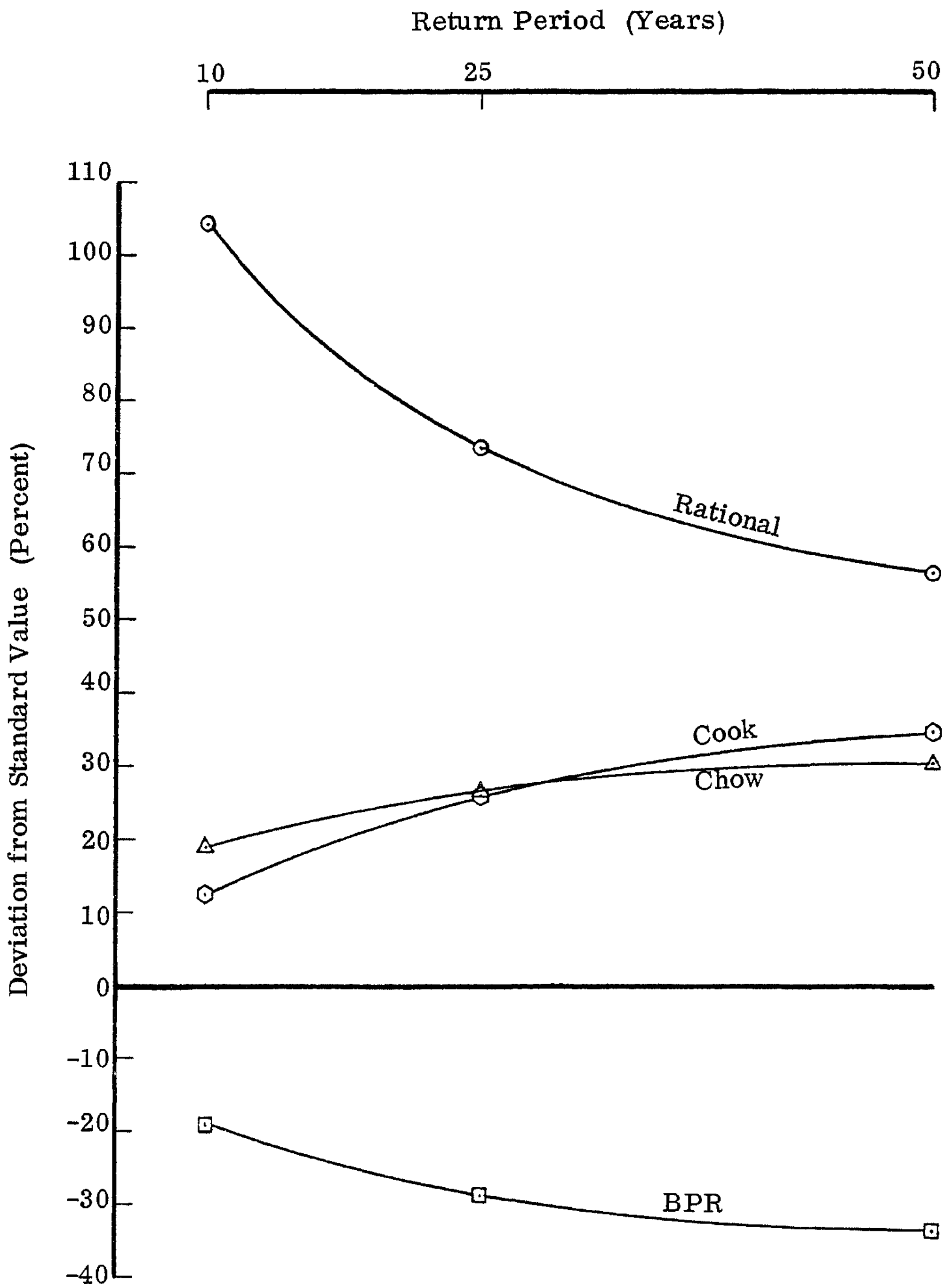

Figure 10. Average Deviations of Predicted Peak Runoff Rates from Standard Values.

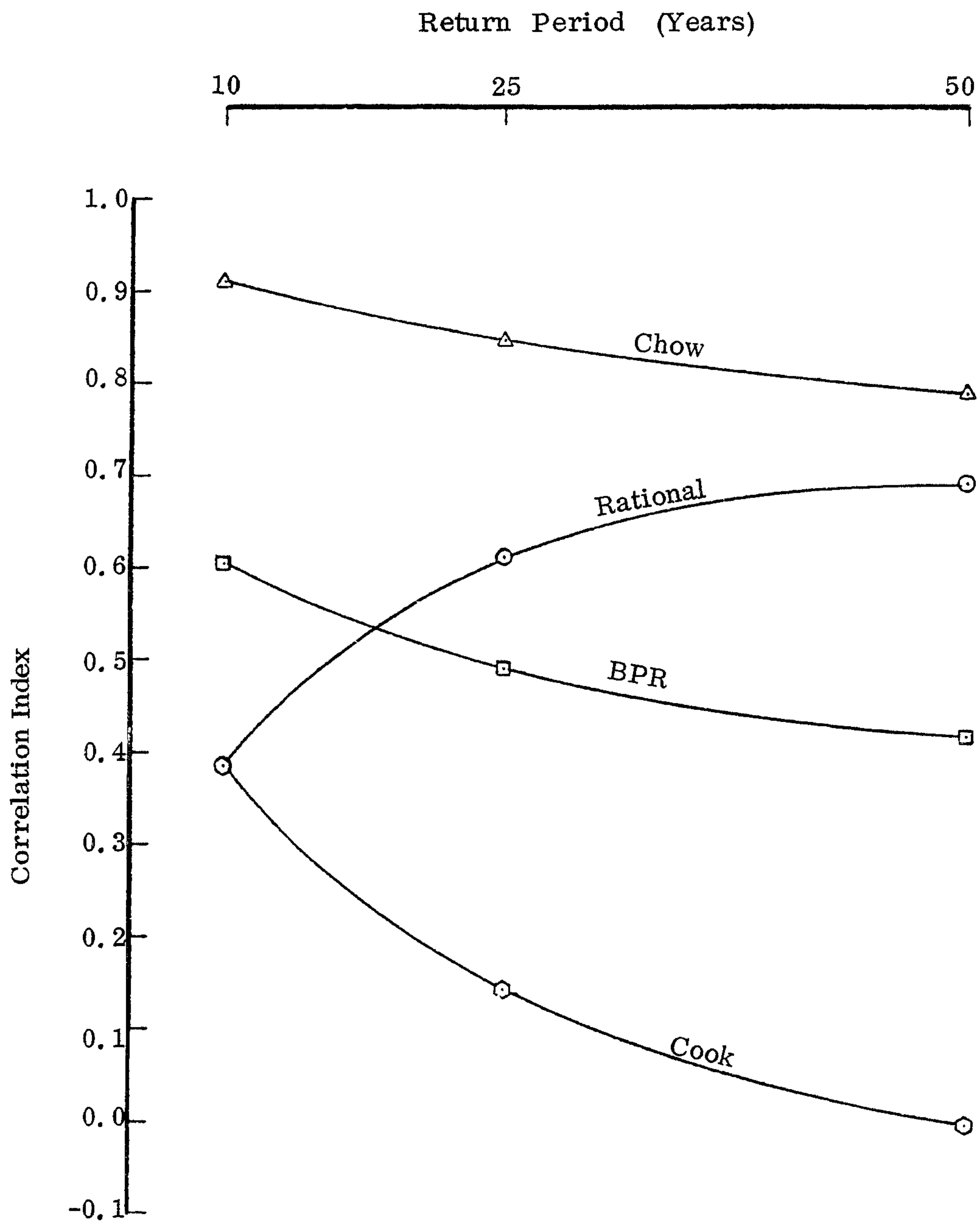

Figure 11. Correlation Index of Peak Runoff Prediction Methods.

APPLICATION OF THE STANFORD STREAMFLOW SIMULATION MODEL TO AGRICULTURAL WATERSHEDS

Introduction

The objective of the Stanford Streamflow Simulation Model developed by Crawford and Linsley (1966) is to describe hydrologic regimes using continuous mathematical relationships among elements of the hydrologic cycle. Digital computers, due to their large storage capacity and high calculating speed, are used to continually update these relationship values. The input parameters may be improved by trial and adjustment until the model is judged to be an adequate representation of the hydrologic cycle for the study area.

A model that reasonably simulates the hydrologic behavior of a watershed could conceivably be a great aid in: analyzing water resources systems; designing local hydraulic structures or waterways; assessing induced climatological changes; quantitizing the hydrologic effects of land use changes such as agricultural practice or urbanization; as well as the classroom teaching of hydrology.

The original Stanford Watershed Model was written in the SUBALGOL language used by the Stanford University Computer Center. James (1966) at the University of Kentucky, translated the Stanford Model III from SUBALGOL to FORTAN IV and also made some modifications of the model. The experience at the Ohio State University with the Stanford Watershed Model started in 1967 when the Kentucky version of the model was obtained and adapted to the Ohio State University IBM 7094 computer system. At this time the model program was flow diagrammed, and the methodology for the use of the program was discussed. After assembling the data, and determining initial basin input parameters, one year of data was applied for Little Mill Creek watershed at Coshocton, Ohio. At this point and for reference purposes the program became the Ohio State University (OSU) version of the Stanford Watershed Model.

In order to continue the work with the model at the Ohio State University it was necessary to convert the OSU version of the program from the IBM 7094 computer system to the recently installed IBM 360 system. After this conversion a sensitivity study was performed using five years of data to determine the best set of basic input parameters for Little Mill Creek, Watershed 97. The model was also applied to five smaller highly instrumented subwatersheds within Watershed 97, using the results of the sensitivity study and five years of data, in an attempt to determine how small a basin can be in which the model is yet applicable.

Brief Review of the Model

A cursory review of the hydrologic concepts employed in the Stanford Watershed Model will be presented. Elaborate details can be found in an expose by Balk and Briggs (1969).

Using basic climatological inputs (hourly precipitation, daily pan evaporation and monthly coefficients), physical watershed parameters (soils surface moisture and retention properties, interflow and groundwater storage and flow conditions, and physical and hydraulic properties of the land and stream channel), the model attempts to simulate the moisture balance in a watershed to produce synthesized streamflow and evapotranspiration.

Referring to Figure 12, a schematic diagram of the hydrologic cycle, three zones of activity are used by the model. The upper zone (soil surface and above) incorporates the processes of interception, transpiration, evaporation, overland flow, surface detention, and depression storage. This zone models the initial watershed response to rainfall and is of prime importance for small storms.

The lower zone (soil between the water table and land surface) activities are infiltration from the upper zone, percolation, and interflow. Its control of infiltration rates influences the simulation of streamflow from major storms.

The deep lower zone (soil below the watertable) determines groundwater flow to the stream, to deep storage, or out of the basin.

As precipitation falls on the watershed it will enter interception storage at a rate depending on the watershed cover. The interception storage volume is recovered continuously at the pan evaporation rate. Excess moisture not directly infiltrated into the soil is simulated as surface detention and overland flow. The value of this upper zone moisture volume is updated every fifteen minutes.

A portion of the water infiltrating from the upper zone is retained in the lower zone with the remainder going to groundwater flow. Moisture in the lower zone may eventually contribute to interflow. Groundwater can pursue a flow path to contribute to streamflow, or pass to deep storage or basin transfer out of the model's moisture balance.

Evaporation and transpiration are continually occurring from all three zones.

A block diagram of the computer program for the model is shown in Figure 13. A detailed flow chart of the Ohio State University version of the model is given by Balk (1968). This current version, written in Fortran IV, has approximately 1500 statements, uses tape loaded data, and takes about two minutes of IBM 360/75 computer time for a 5-year period run with a binary source deck.

Model Input and Output

In addition to the program control options and climatological data there are 38 input parameters required by the model. A dictionary of the input variables is given in Table 8. Detailed procedures for evaluating these parameters are given by Balk (1968). Their relative influence is discussed in a sensitivity study performed by Briggs (1969). Although all parameters are adjustable there are only about five, mainly those not directly identifiable from the geomorphology of the area, that are usually varied to achieve better simulation. Towards the end of the adjustment period only two or three moisture balance parameters are subject to change.

From an engineering viewpoint, there are parameters which could be varied to reflect watershed changes induced by agricultural practices.

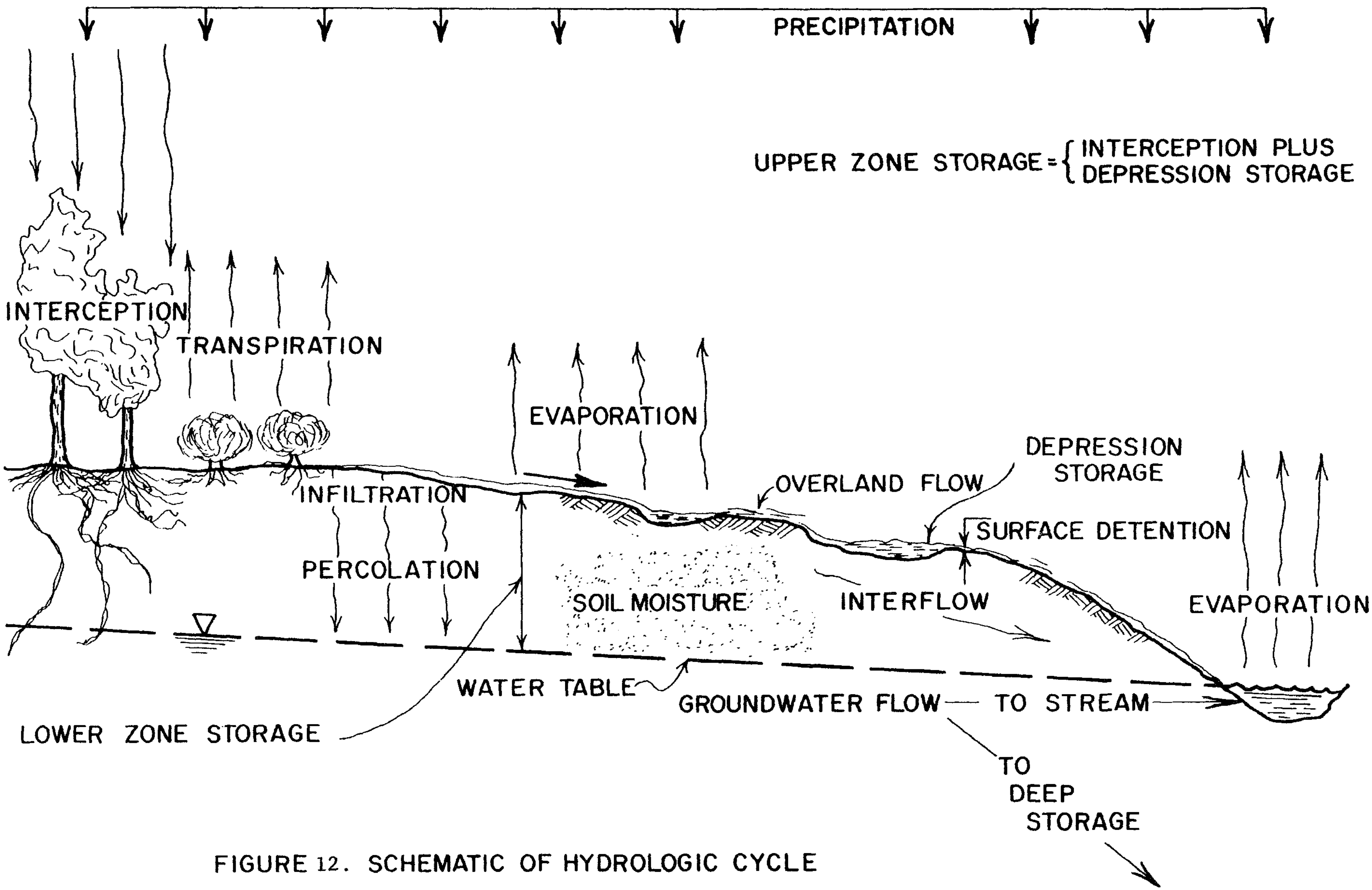

FIGURE 12. SCHEMATIC OF HYDROLOGIC CYCLE

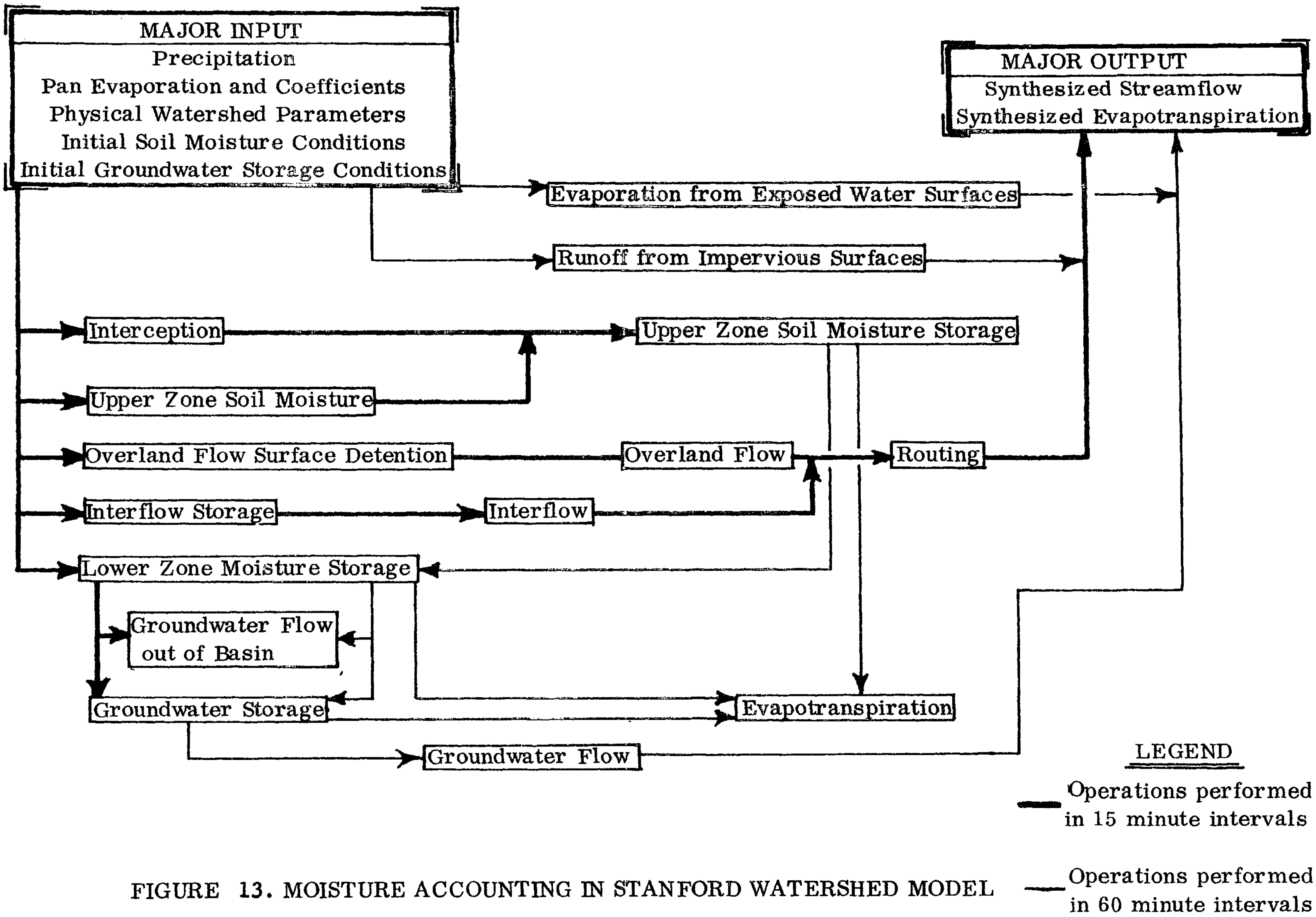

FIGURE 13. MOISTURE ACCOUNTING IN STANFORD WATERSHED MODEL

TABLE 8. DICTIONARY OF INPUT VARIABLES

VARIABLE	UNITS	DEFINITION
A	-	Impervious fraction of watershed surface
AREA	sq. mi.	Subwatershed drainage area
C	-	Time-area histogram data
CB	-	Infiltration index
CHCAP	cfs.	Index capacity of stream channel
CX	-	Index for soil surface moisture storage
CY	-	Interflow index
DD13	-	No. of days of input rainfall
EDF	-	Index for soil surface moisture storage
EF	-	Evaporation-infiltration factor
EN	-	Factor varying infiltration by season
EMIN	-	Minimum value for EN
EPXM	in/hr	Maximum interception rate for dry watershed
ETL	-	Factor of total watershed in stream surface
GWS	-	Current value of groundwater slope index
INUM	-	No. of days of detailed storm output
IOUT	-	Initial day no. for storm details
IRC	-	Daily interflow recession constants
KK24	-	Daily baseflow recession constant
KSC	-	Routing parameter for low flows
KSF	-	Routing parameter for flood flows
KV24	-	Baseflow recession adjustment factor
K1	-	Rainfall weighting factor for basin
K24EL	-	Groundwater evaporation parameter
K24L	-	Index for groundwater flow leaving basin
K3	-	Soil evaporation parameter
L	ft.	Mean overland flow path length
LZS	in.	Current soil moisture storage
LZSN	in.	Soil moisture storage index
NN	-	Manning's n for overland flow on soil area
NNU	-	Manning's n for overland flow on impervious area
RFC	-	Index for routing
SGRT	-	Hour of day in which raingage read
SGW	in.	Groundwater moisture storage
SS	-	Average groundwater slope
U	in.	Time of concentration
UZS	in.	Current soil moisture storage
WSG	-	Storage gage weighting factor
Z	-	Time-area histogram elements

Features such as crop type, cultivation method, terracing, channel improvements,surface and subsurface drainage installations, wells, irrigation, evaporation suppressants, etc. can be investigated with the model.

There is considerable information regarding the soil moisture balance in the watershed at anytime during the simulation period that can be printed out by simple program modifications. The current OSU version of the model will produce basic synthesized output tabulations of average daily streamflow, end of the month moisture distributions, parameter indices, annual watershed yields, evapotranspiration, and statistical data on the simulation success. Through the use of the program control options, additional output such as the detailed performance of specified storms and superimposed computer plots of the actual and synthesized streamflow can be obtained.

Application to Agricultural Watersheds

Although the model was designed for usage on large watersheds, Clarke (1968), Crawford and Linsley (1966), Drooker (1968) and Moore, et al. (1969) have applied it to smaller rural and urban watersheds with reasonable success. Research with the model at the Ohio State University was conducted mainly on small agricultural watersheds in an attempt to evaluate its applicability to such watersheds.

Six well instrumented and monitored watersheds at the North Appalachian Experimental Watershed, Coshocton, Ohio were chosen to test the model. The area is representative of the unglaciated agricultural lands of the Allegheny Plateau. Bed rock outcrops are sedimentary composed mainly of horizontal beds of sandstone and shale with some coal and clay. The soil mantle, generally ranging in depth from one-half to 8 feet, is principally a Muskingum-Keene silt loam.* A humid climate with annual average temperatures of 52 degrees, precipitation of 39.5 inches, evapotranspiration of 25 inches, and a snowfall (approximately 5 percent of the precipitation) of 19 inches prevails on the watersheds.

The watersheds of the Little Mill Creek basin used in this study ranged in size from 4580 to 122 acres. The area of each watershed and its land use distribution are listed in Table 9. Final input parameters are given in Table 10. Table 11 lists the time-area histogram data for the routing calculations used in this study.

Table 9. Area and Distribution of Cover in Test Watersheds.

WATERSHED	97	95	94	92	5	10
AREA (acres)	4580	2570	1520	920	349	122
COVER	Percent of Watershed in Land Use					
Cropland	18	15	15	16	20	21
Grassland	50	55	55	59	54	48
Woodland	28	26	26	21	23	25
Miscellaneous	4	4	4	4	3	6

*Current updating of the soils map of the area may find new names for these soils.

TABLE 10. FINAL INPUT PARAMETERS

Model Parameter	Parameter Value					
	W/S 97	W/S 95	W/S 94	W/S 92	W/S 5	W/S 10
A	0.0	0.0	0.0	0.0	0.0	0.0
AREA	7.16	4.02	2.37	1.44	0.55	0.19
CB	0.85	0.85	0.85	0.85	0.85	0.85
CHCAP	800.0	800.0	800.0	800.0	800.0	800.0
CX	0.40	0.40	0.40	0.40	0.40	0.40
CY	3.0	3.0	3.0	3.0	3.0	3.0
DD13	0.0	0.0	0.0	0.0	0.0	0.0
EDF	0.85	0.85	0.85	0.85	0.85	0.85
EF	4.0	4.0	4.0	4.0	4.0	4.0
EMIN	0.50	0.50	0.50	0.50	0.50	0.50
EPXM	0.15	0.15	0.15	0.15	0.15	0.15
ETL	0.0	0.0	0.0	0.0	0.0	0.0
GWS	0.20	0.20	0.20	0.20	0.20	0.20
IRC	0.001	0.001	0.001	0.001	0.001	0.001
KK24	0.95	0.95	0.95	0.95	0.95	0.95
KSC	0.94	0.94	0.94	0.94	0.94	0.94
KSF	0.98	0.98	0.98	0.98	0.98	0.98
KV24	0.75	0.75	0.75	0.75	0.75	0.75
K1	1.0	1.0	1.0	1.0	1.0	1.0
K24EL	0.0	0.0	0.0	0.0	0.0	0.0
K24L	0.0	0.0	0.0	0.0	0.0	0.0
K3	0.20	0.20	0.20	0.20	0.20	0.20
L	470.0	525.0	570.0	600.0	463.0	546.0
LZS	15.0	9.6	9.6	9.6	9.6	9.6
LZSN	20.0	12.0	12.0	12.0	12.0	12.0
NN	0.37	0.37	0.37	0.37	0.37	0.37
NNU	0.015	0.015	0.015	0.015	0.015	0.015
RFC	1.5	1.5	1.5	1.5	1.5	1.5
SGW	0.10	0.10	0.10	0.10	0.10	0.10
SS	0.16	0.15	0.132	0.14	0.144	0.145
UZS	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 11. TIME-AREA HISTOGRAM DATA

Watershed	97	95	94	92	5	10
C, Actual time of conc.	162.0	84.4	59.1	32.0	17.4	13.5
U, Model time of conc.	165	90	60	30	15	15
Z, Number of elements	11	6	4	2	1	1
Elements of the Time-Area Histogram	0.032	0.062	0.183	0.534	1.000	1.000
	0.058	0.135	0.242	0.466		
	0.072	0.250	0.318			
	0.084	0.220	0.257			
	0.085	0.185				
	0.078	0.148				
	0.103					
	0.152					
	0.136					
	0.111					
	0.089					

Results of the Study

A partial summary of the final simulation results of the study watersheds for a five-year period is given in Table 12. It lists the synthesized yield, showing the percent over and under-synthesized when compared with the recorded yield, and the average daily streamflow correlation coefficients.

The results indicate a trend for the yield to be oversynthesized for the smaller watersheds and an overall general increase for all the watersheds with each successive year of the study period. This is due to the model adjusting itself as it reaches an equilibrium in its soil moisture balance. Experience has shown that at least 3 years of modeling are needed for the adjustment period.

Figure 14 is a typical computer output plot of the hydrographs for a watershed after two prior water years of adjustment running. Winter and

TABLE 12. ANNUAL YIELD VOLUMES AND CORRELATION COEFFICIENTS

Watershed	97		95		94		92		5		10	
	Yield	r	Yield	r	Yield	r	Yield	r	Yield	r	Yield	r
Water Year	(%)		(%)		(%)		(%)		(%)		(%)	
1958-59	-30.3	0.98	-24.9	0.99	-30.2	0.98	-26.7	0.98	-21.0	0.98	- 1.3	0.98
1959-60	-2.8	0.82	- 8.6	0.78	- 7.8	0.74	+ 2.5	0.73	+ 2.6	0.70	+25.8	0.76
1960-61	-12.3	0.91	-20.7	0.88	-18.2	0.89	-15.8	0.87	+ 0.2	0.81	+ 7.1	0.91
1961-62	+ 0.4	0.63	- 8.5	0.65	-15.8	0.66	- 7.0	0.65	+ 5.6	0.65	+19.5	0.61
1962-62	+ 9.1	0.91	- 0.5	0.92	- 2.0	0.92	+ 4.9	0.90	+30.8	0.92	+25.8	0.93

KEY: - undersynthesized, + oversynthesized, r correlation coefficient

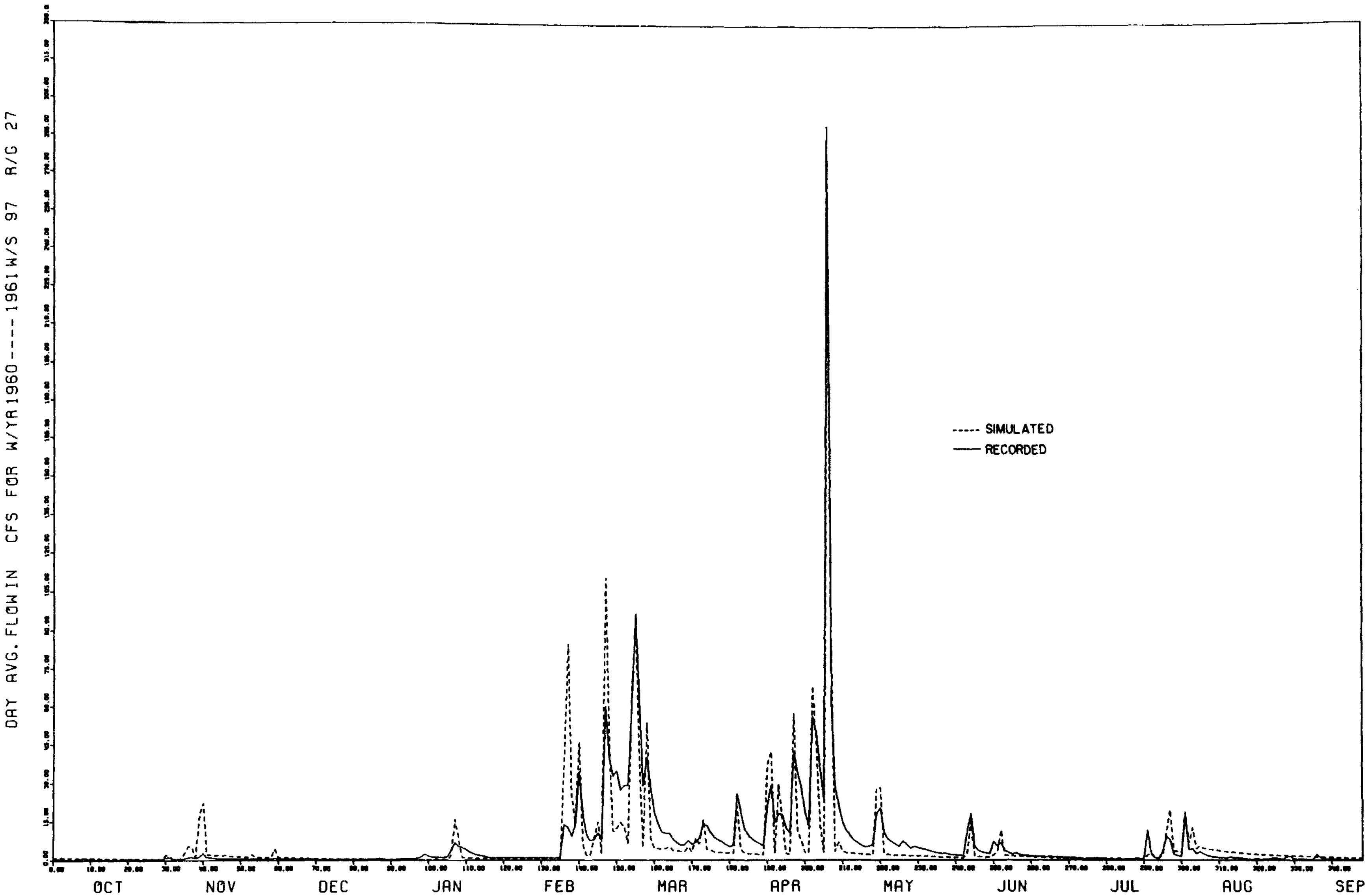

Figure 14. Streamflow Hydrographs for Watershed 97.

spring recession flows were undersynthesized. Attempts to increase the recession flows to meet the recorded values were unsuccessful. This is not surprising because the complicated geology of the Coshocton watersheds produces groundwater behavior which is difficult to define.

The average daily streamflow correlation coefficients are largely controlled by the degree of matching between the synthesized and recorded peak flows. Since the watersheds used are relatively small and the rainfall is moderate, the average peak flood flows were not extremely large. Very low-flow volumes in the summer are due to the short duration convectional (thundershower) storms which do not produce extended streamflow, dry soil conditions, and high evapotranspiration rates.

Table 12 shows that, overall, the correlation coefficients for each water-year were rather stable for the particular watershed modeled. The poorer correlations can be partially attributed to the oversynthesized streamflow in the autumn. No logical explanation can be offered at this time for this behavior which is quite consistent in the study period. A possible explanation is that the actual soil moisture may be extremely lower than the modeled value during this season due to very dry summer conditions, thus allowing the soil to absorb the rainfall. Inquiry into agricultural practices in the autumn failed to explain these events.

Snowmelt is a serious problem not to be overlooked when applying the model to watersheds in a temperate climate. Due to the lack of necessary data (daily maximum and minimum temperatures, dewpoint, snow evaporation, short wave radiation, and wind velocity) the original snowmelt subroutine of the Stanford Model is not functioning in the OSU version. Consequently, the model treats all forms of precipitation as rainfall entered at the time of occurrence.

Upon comparison of the synthesized and recorded streamflow hydrographs and the corresponding recorded average daily temperatures, the effects of snowfall, frozen ground, and eventually snowmelt were quite significant. The model immediately produced streamflow runoff from the precipitation (snow) which actually contributed to streamflow days and, in some cases, weeks later.

In most situations the snowmelt and frozen ground problem was extended beyond the few days of peak hydrograph streamflow. Due to what seems to be frozen and partially frozen ground, the watershed does not react normally to runoff and groundwater. Rainfall during a period of partially frozen ground will contribute to streamflow through overland runoff as a result of water being unable to infiltrate into the soil. Therefore, the modeled groundwater soil moisture will not be representative of the actual watershed conditions.

After snowmelt problems in the winter, the larger hydrograph peaks in the ensuing months will match recorded values with acceptable accuracy but there is a definite problem in getting the undersynthesized smaller peaks and recession flows to match the recorded streamflows. After two or three consecutive years of data are processed there is a trend for the model to improve in synthesizing recorded streamflow except where freezing temperatures and snowfall intervene.

In an attempt to rectify the obvious snowmelt situations, precipitation data recorded as snow was transferred systematically to the later date. The temperature critique method used was not extremely accurate but proved applicable to other years. It was deemed much more acceptable than leaving the data as an input of precipitation at the time of occurrence as the records would indicate.

The routing technique used in the model is based on translating the stream inputs to an imaginary reservoir at the basin outlet and then routing by level pool methods. Since the entire system is taken as linear, the time-area method presented by Linsley et al. (1958) is employed in the model routing.

Using Watersheds 92 and 5, a study was made changing the number of elements in time-area histogram to determine the effect of the simulated streamflow. The number of elements for Watershed 92 was decreased from two to one for Watershed 5. The results showed that the synthesized daily correlation coefficients did not change significantly.

While changing the number of elements in the time-area histogram, the 15-minute flows for a particular storm were obtained by a program option. It was observed that the 15-minute storm streamflow magnitudes increased indicating a forward time shift in streamflow for the fewer number of elements with no detectable alteration in the average daily amount of streamflow.

The smallest watershed studied was Watershed 10 (122 acres). Its calculated time of concentration using the formula of Kirpich (1940) was 13.5 minutes. The model has streamflow routing based on a minimum of a 5-minute time of concentration interval. Therefore, a time of concentration of 15 minutes was adopted for Watershed 10. The criteria (runoff yield, daily soil moisture values, hydrograph peaks values, hydrograph recession flows, and daily correlation coefficients) for judging the performance of the model on the five larger watershed were equally satisfied for Watershed 10. Thus, as the model is currently programmed the smallest watershed applicable must have a time of concentration of at least 15 minutes. Drooker (1968) reports that a New England watershed of about 30 acres with a 15-minute time of concentration has been reasonably simulated by the Stanford Model.

Discussion

A goal of the research, using the Stanford Streamflow Simulation Model, performed at the Ohio State University during the last couple of years, was to progress the model toward eventually becoming a tool for the practicing engineer. It is important to stress that a user of the model recognizes its abilities and drawbacks. It has been found that with adjustment of input parameters, the model can simulate with fair accuracy the streamflow yield volume. However, in so doing, some aspects of the streamflow may not be well correlated. According to the user's objectives, the model can be adjusted for better simulation of peaks or recessions flows.

A greater understanding and appreciation of the model will be realized if the input parameters are viewed in relation to the equations in which they are involved, and not as mere numbers that permit a computer program to return undeniable results.

Application of the model to six agricultural watersheds for five years of record showed that the model does reasonably simulate average daily streamflow. Also, for this study the model's performance was not hindered by the size of the smallest watershed (122 acres). The model failed to simulate the autumn rainfalls with no definite explanation yet available for this behavior.

The occurrence of snowmelt is still a serious problem with the OSU version of the model. To rectify this situation, obvious snow precipitation can systematically be moved to a later date.

A serious drawback to using the model is the time required to become acquainted with the model in order to interpret the output and make the proper adjustments of the parameters. Briggs (1969), through a sensitivity study, has attempted to provide some user's guidelines for adjustment of the more pertinent parameters.

The model's size dictates that a high speed and large storage capacity digital computer be available. In order for a user to become familiarized with the model and determine the best basin parameters, much computer time might be required. Our experiences indicated that 20 to 50 runs may be needed. At 2 minutes a run, this can be costly.

In conclusion, the Stanford Streamflow Simulation Model appears to form a sound and workable foundation for streamflow simulation work, including agricultural watersheds.

A STOCHASTIC APPROACH TO OVERLAND FLOW

Introduction

The hydrology of surface waters is characterized by the multiplicity of prediction formulas that have been devised to facilitate the estimation of runoff rates and volumes. Unfortunately, each of these formulas is applicable for a specific set of conditions and, therefore, an attempt to apply a given formula without due regard to the conditions for which it was developed may lead to erroneous results.

Hydrologists do not have at hand a general functional form relating watershed runoff to the climatic and physiographic parameters that must be used to describe the runoff process. Even more important, no analytic means of defining the proper parameters for a general functional form are available.

A framework on which to build analytical techniques is necessary for defining and examining the importance of the essential parameters. It is felt that surface roughness may be a significant parameter in describing runoff from small watersheds.

Because of the difficulty in using the Navier-Stokes equation to model particular overland flow conditions, it was thought that fluid motion could be studied in terms of discrete globules whose motions follow descriptions similar to those used for Brownian motion. This Brownian motion approach may be feasible if the random walk nature of the path of a rill or rivulet of water on a watershed surface is accepted. If this approach is possible, insofar as the velocity of the fluid globules is concerned, the results will be interpreted only probabilistically.

With reference to a particular fluid globule, several things may happen. The globule could (1) be retained on vegetation and never enter the runoff process, (2) evaporate during the runoff process, (3) be retained in depressions on the surface, (4) infiltrate into the soil mass, or (5) make its way over the surface and become part of the runoff. For the purposes of this analysis it was assumed only that all fluid globules under consideration become runoff. This simplification permitted the development of a model in which probabilistic parameters of the velocity of a fluid globule are analytically related to measurable watershed parameters.

Assumptions

Two groups of assumptions were made; the first group was with respect to the watershed surface and the second group was with respect to the motion of a mass particle over the surface. These assumptions are stated as follows:

1. A watershed is assumed to be a planar surface upon which random irregularities are superimposed.

2. For a given planar watershed unit, the irregularities are assumed to be statistically homogeneous and isotropic, i.e., the nature of the irregularities is the same regardless of the position and direction one takes on the surface.

3. The watershed is assumed to be modeled by a two-parameter stochastic process whose first- and second-order statistics are Gaussian.

4. The condition of ergodicity is assumed to apply; i.e., the parameters necessary for the probabilistic description of an ensemble of surfaces can be estimated from physical measurements of a single realization of a surface.

5. A mass particle is assumed to undergo dissipative motion on a surface where the velocity-proportional drag forces are of sufficient magnitude that the particle always remains in contact with the surface.

6. The driving forces acting on the mass are stochastic in nature owing to the surface. These include a force per unit mass which is correlated to the surface irregularities, and a force per unit mass which is an impulse type force due to particle interaction and the presence of foreign objects on the surface, such as stones or grass stalks.

7. Initial conditions are such that the particle does not lodge or become trapped on the surface, but continues to move, dissipating energy until it passes out of the area of interest.

8. The average velocity of a large group of particles is the same as the average velocity of a single particle taken over a long travel time.

9. An equation similar to the Langevin equation of Brownian motion is assumed to describe the motion of a single particle.

The Postulated Equation

Based on the above assumptions, a Langevin type equation was postulated to describe the motion of a fluid globule, a discrete mass particle, on an impermeable watershed surface as:

$$\frac{d\, v(r,t)}{d\, t} + \beta v(r,t) = f_g(r) + \overline{F}_g + F_I(r) \quad . \quad . \quad . \qquad (4)$$

where $v(r,t)$ is the velocity of a particle which is at position r at time t, and β is a constant scalar frictional coefficient; $f_g(r)$ is the fluctuating portion of the stochastic surface impressed force, expressed as a function of position, and $\overline{F}_g$ is the constant force related to the mean slope; $F_I(r)$ is assumed to be an impulse-type force that occurs as a result of globule interactions with other globules, or with foreign elements on the surface such as stones or vegetation. Assuming that the impulse-type force, $F_I(r)$ is negligible, expressions were developed for the surface impressed forces $f_g(r)$ and $\overline{F}_g$. No solution was found for equation (4)

Preliminary Investigation

A preliminary investigation was carried out to check the assumption that the irregularities on a watershed surface are statistically homogeneous and isotropic. In Figures 15 and 16 appear the results of this preliminary investigation, using power spectrum techniques, of the roughness at two locations on a third-year alfalfa meadow. Two spectra were obtained at each point, one from a profile taken down the slope, and the other from a profile across the slope. Although it is by no means conclusive, the presence of peaks in the spectra indicates the appearance of an element of periodicity in the roughness. The power concentrated at one cycle per meter is at about the proper frequency to result from roughness coming through the planting and cultivation of corn. Another definite periodicity is apparent at six cycles per meter. This might result from hand seeding practices of agricultural crops, such as alfalfa.

The spectra were computed primarily to check the degree of homogeneity and isotropy to be expected under natural conditions. The reasonably good agreement in the range of up to four cycles per meter would indicate that, in this range at least, the surface is relatively stable in both directions over the range of slopes at the locations where measurements were taken. Some deviation is noted at higher frequencies. No conclusions should be drawn from these data since analysis of many surfaces should be performed before questions of isotropy and homogeneity can be resolved.

The assumption that the absolute value of the magnitude of the gradient with respect to the mean slope would not exceed 0.2 was examined using a probability graph of the gradients as given on Figure 17. It is to be noted that the percentage of gradients exceeding 0.2 in absolute value is less than two percent, indicating that the stochastic surface impressed force can be linearized. The data appear to fit a Gaussian distribution; however, many surfaces should be examined to better establish the validity of the above assumptions.

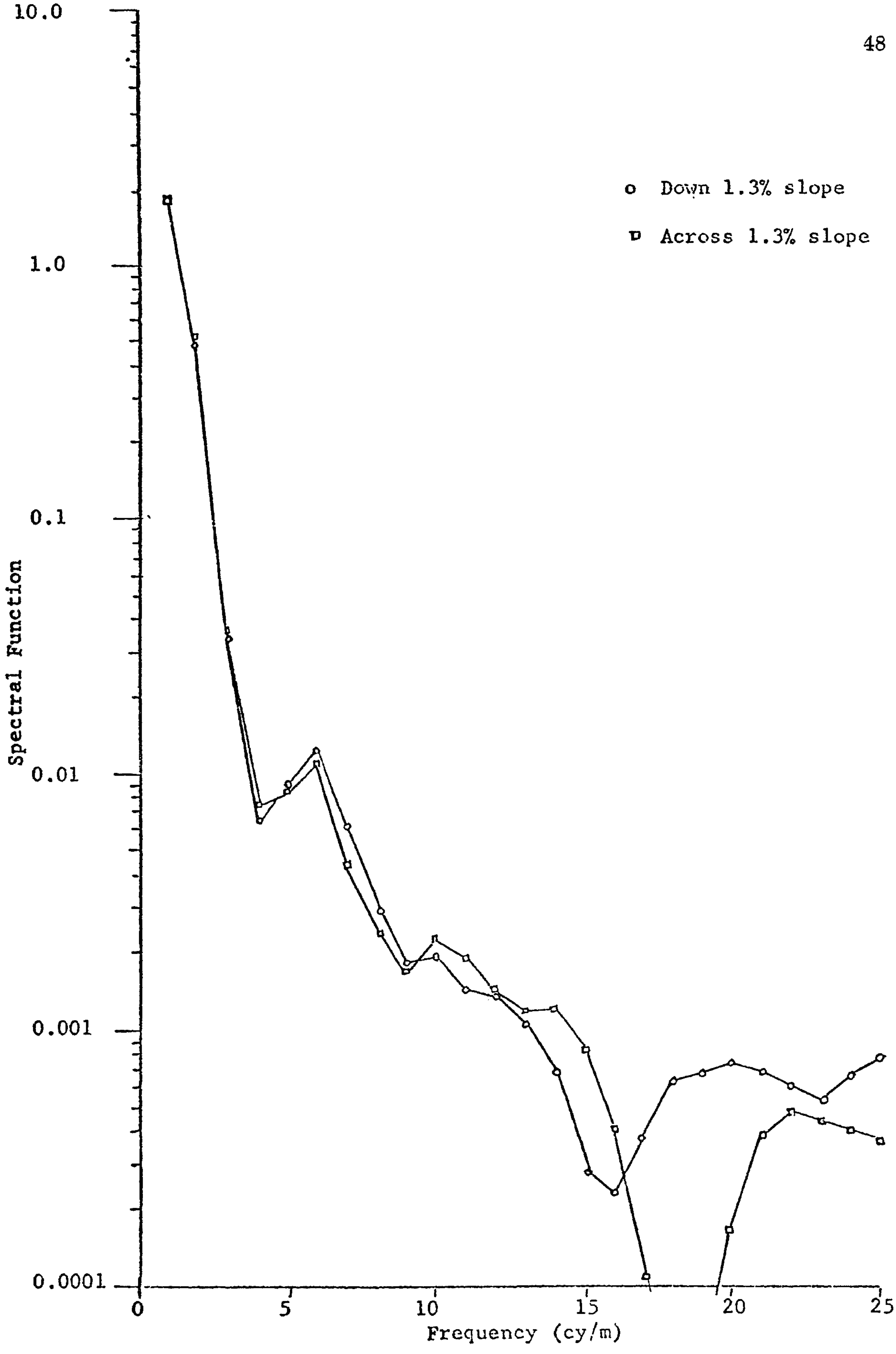

Figure 15. Spectra of Surface Roughness from Third-Year Alfalfa Meadow with Down-and Across-Slope of 1.3 percent.

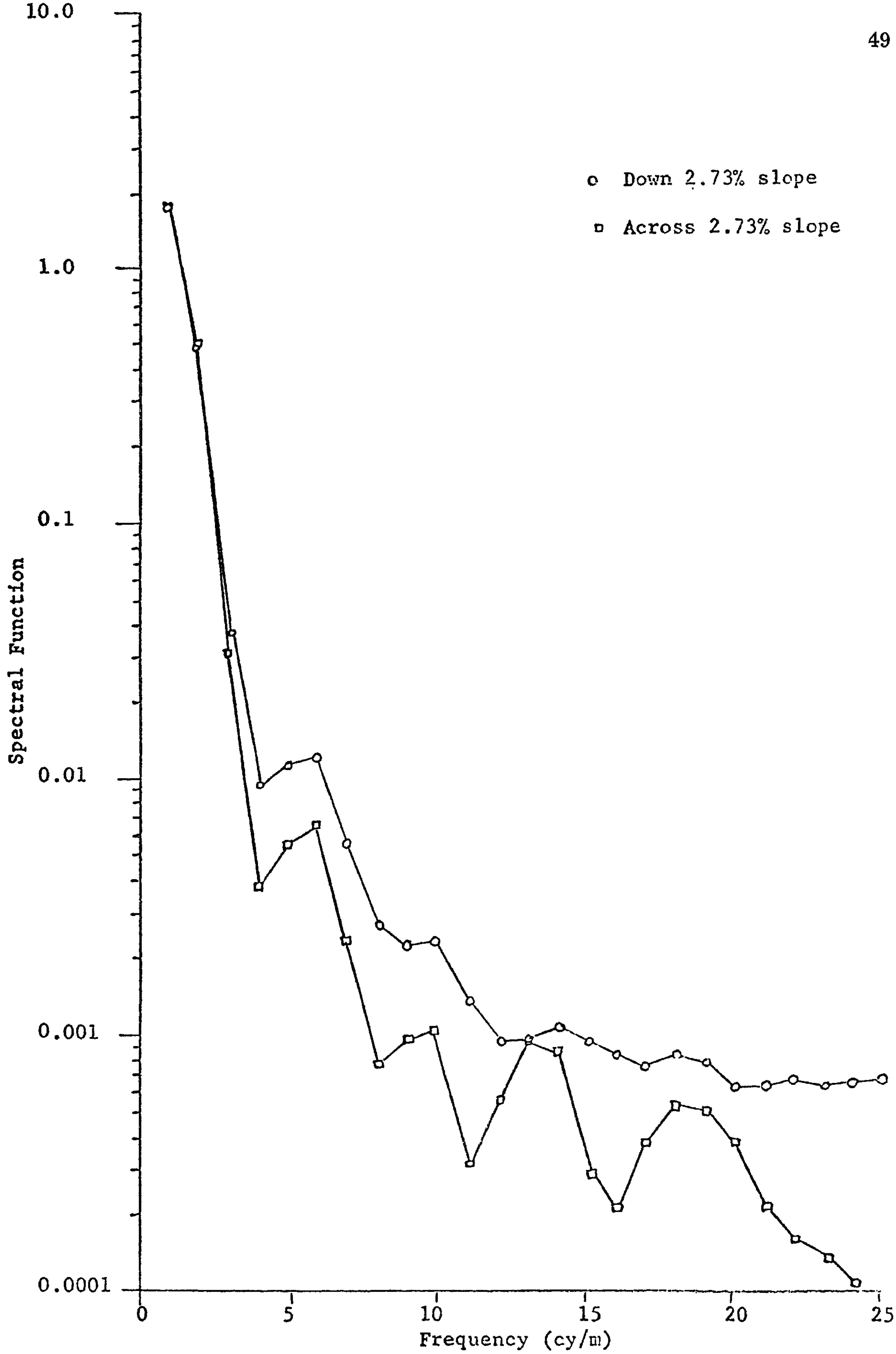

Figure 16. Spectra of Surface Roughness from Third-Year Alfalfa Meadow with Down- and Across-Slope of 2.73 percent.

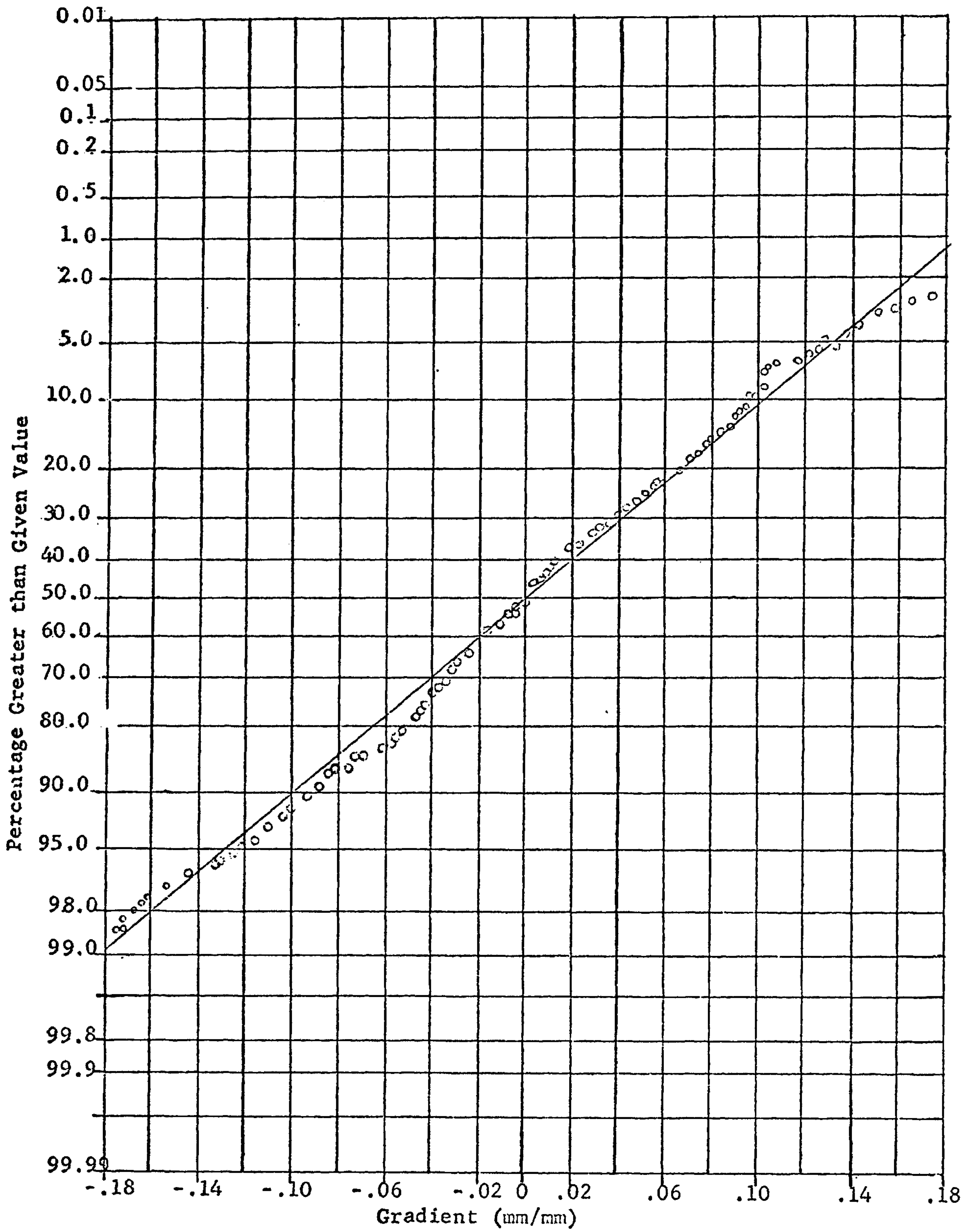

Figure 17. Normal Probability Graph of Surface Gradients with Respect to the Mean Slope.

Conclusions

Analytical details and data can be found in a dissertation written by Merva (1967). Major conclusions were:

(1) The nonlinearity of the runoff process makes it unlikely that the phenomenological structure of nonequilibrium thermodynamics could be directly applied to runoff prediction.

(2) For constant mass particles where useful output is defined as motion of the center of mass, the rate of energy degradation separates into that associated with the center of mass motion, and that going with motions about the center of mass.

(3) It is possible to obtain a model of an impermeable watershed surface in terms of a two-parameter stochastic process.

(4) Assuming contact at only one point, the surface-impressed component of the gravitational attraction force can be expressed as a vector in terms of the normal to the surface and the gravitational attraction vector acting on a mass particle.

(5) Under the limitation that the roughness slopes taken with respect to the mean plane of the surface are not larger than 0.2 absolute value, the surface impressed component of the gravitational force is a stationary stochastic process correlated to the surface.

RUNOFF SIMULATION WITH A MODEL DEVELOPED BY HUGGINS AND MONKE

A Brief Review of the Model

General Concepts. Most watershed models are "lumped" hydrologic system models. This means that the areal distribution and variability of the rainfall and watershed parameters are not considered. Thus, the lumped parameter approach has built-in limitations, particularly in the lights of the complexity of the hydrologic system.

To overcome the above limitations, Huggins and Monke (1966) developed a watershed model based on a distributed system analysis. The watershed was divided into a finite number of elements. The size of the elements was such that the important hydrologic parameters such as rainfall, infiltration rate, slope magnitude and direction, and vegetation are uniform within each element. These parameters could vary between elements. Figure 18 shows a hypothetical watershed sub-divided into elements. The outflow from one element becomes the inflow to the adjacent element. The flow within each element is assumed to be along the direction of the steepest slope of that element. The method by which the outflow from an element is proportioned between its two adjacent elements is shown in Figure 19. This approach, therefore, requires the development of a runoff hydrograph for each element and the integration of all the responses over the entire watershed.

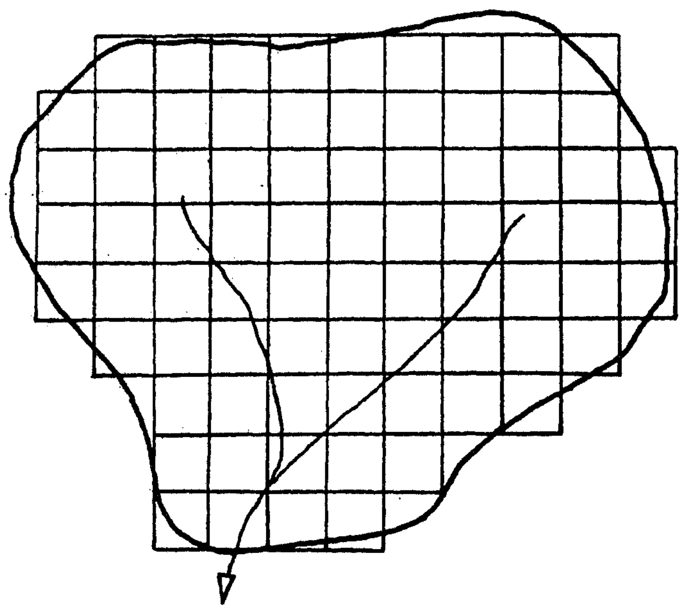

Figure 18. Hypothetical Watershed Showing Subdivision into Elements. (After Huggins and Monke (1966)).

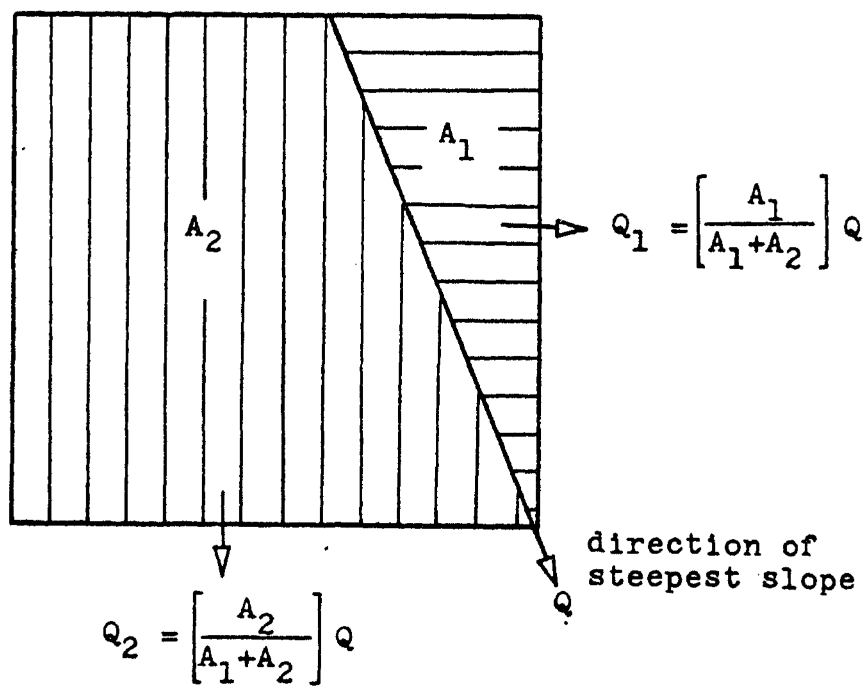

Figure 19. Surface Flow Conditions Within an Element (Huggins and Monke (1966)).

The continuity equation

$$I - Q = ds/dt \qquad (5)$$

where

I = inflow rate

Q = outflow rate

s = volume of water in storage within the element

t = time

was applied to each element to obtain the relationship between the response of individual elements to the composite watershed hydrograph. For computational purposes equation 5 was used in the form:

$$I_1 + I_2 - Q_1 + 2s_1/\Delta t = Q_2 + 2s_2/\Delta t$$

where subscript 1 refers to the values at the beginning and subscript 2 refers to the values at the end of a time increment Δt. Starting from the time of known initial conditions, equation is applied sequentially and repeatedly to all points until the complete hydrograph is obtained at the outlet of the watershed.

Interception. The rate of interception was computed as the percentage of the product of the rainfall rate and the horizontal projected leaf surfaces. The projected leaf coverage areas for the required crops were obtained from literature.

Infiltration. An empirical infiltration equation suggested by Holtan (1961) and Overton (1964) was modified for the watershed model. The modified equation is

$$F = f_c + A\left[(s-F)/T_p\right]^B$$

where

f = infiltration capacity at a particular time

f_c = steady-state infiltration capacity

A, B = coefficients characteristic of a given soil and its antecedent condition

s = storage potential of the soil within the infiltration control zone (total porosity minus antecedent soil moisture)

T_p = total porosity of the soil above the impeding layer

F = total volume of water infiltrated.

The infiltration constants, A and B, were determined from observed data by least square regression analysis.

Surface Runoff. For the surface runoff computation a functional relationship was assumed to exist between the depth of water and the rate of surface runoff at every point within the watershed. This relationship is given by

$$V = \bar{d}^{m}$$

where

V = average flow velocity

$\bar{d}$ = average cross-sectional flow depth

$K = \frac{1.486 \sqrt{s}}{n}$ (from Manning's equation)

m = 2/3

s = slope of watershed element

n = hydraulic roughness coefficient.

Surface Storage. The volume of surface storage in each element was expressed as a function of the depth of water in the element. This function was expressed in the form of an empirical dimensionless equation

$$y = s/s_u$$

where

$y = s/s_u$

s = storage volume at any time

s_u = surface storage when $h = h_u$

$x = h/h_u$

h = depth of depression at any point

h_u = maximum value of h

A,B = coefficients.

The coefficients A and B were obtained by regression analysis of experimental data.

Interflow. Interflow was assumed to be negligible due to the geology and soils of the area studied.

Application of the Model to Coshocton Watersheds

Four of the small Coshocton watersheds, watershed 106, 115, 121, and 123, were selected for testing the model. The storms of June 12, 1957 and April 25, 1961 were applied to watersheds 115 and 123; and the storms of August 23, 1944, June 13, 1960, and May 13, 1964 were applied to watersheds 106 and 121. Some of the watershed parameters are shown in Table 13. Figure 20

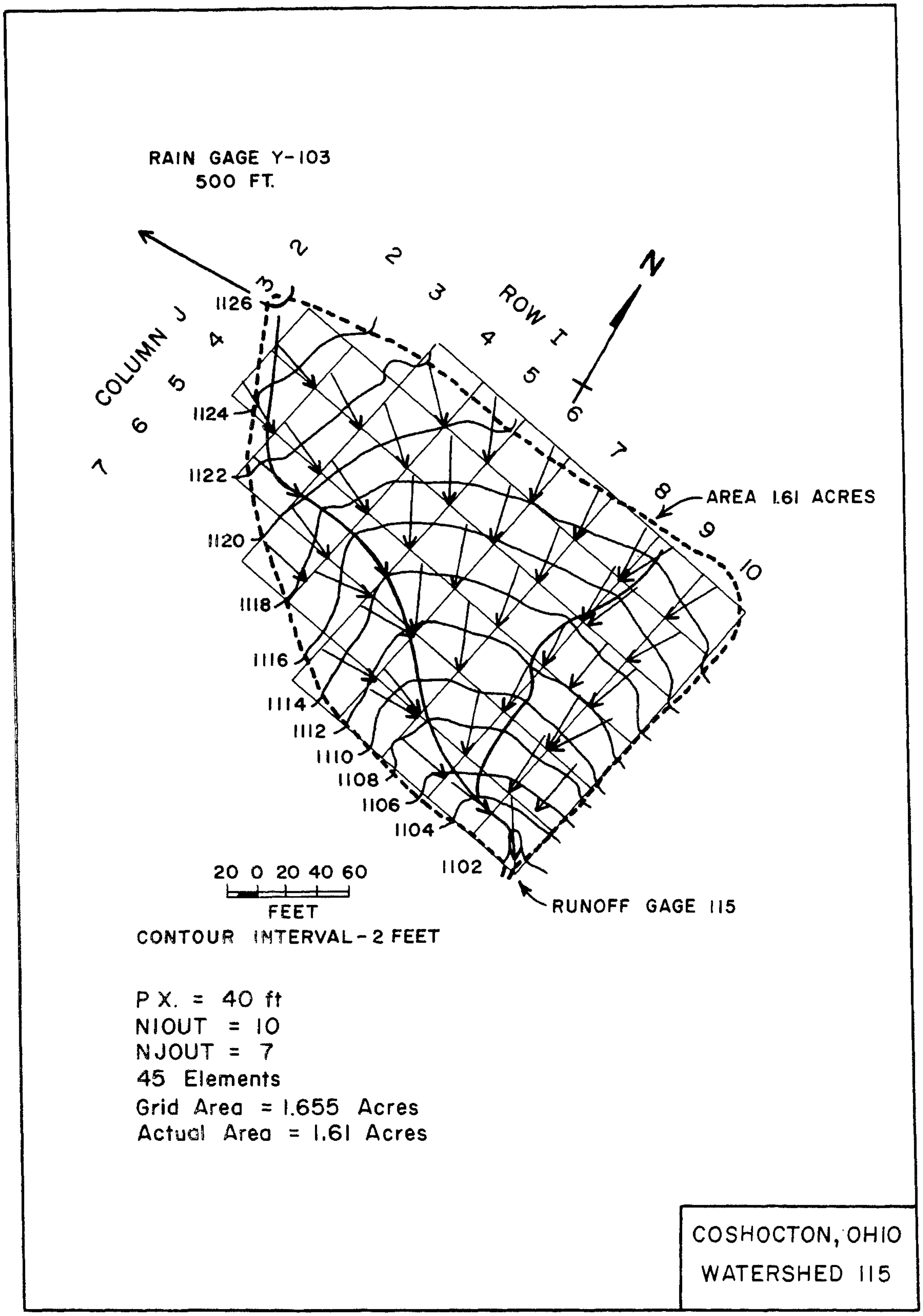

Figure 20. Elements with Their Directions of Greater Slope for Watershed 115.

Table 13. Four Coshocton Watersheds and Some of Their Parameters.

Watershed No.	Area acres	Type of Crop Grown	Soil Type*	Time of Concentration (min)
106	1.56	Corn	Muskingum Loam	1.20
115	1.61	Corn	Keene Silt Loam	2.70
121	1.42	Corn	Muskingum Loam	1.25
123	1.37	Corn	Keene Silt Loam	3.00

*Current updating of the soils map of the area may find new names for these soils.

shows watershed 115 together with its elements. The arrows are in the direction of greatest slope for each element.

The definition and units of some of the variables are shown in Table 14. Some of these parameters were varied to study their influence upon the simulation results. The values of these variables used to simulate the storms of June 12, 1957 and April 25, 1961 on watershed 115 are shown in Tables 15 and 16, respectively.

Table 14. Definitions and Units of Some of the Model Variables.

Variable	Units	Definition
ADIR	in.	Surface retention depth
ASM	--	Antecedent soil moisture (percent of saturation)
DINF	in.	Depth of the control zone used in calculating the infiltration capacity rates
DT	sec.	Time increment
DX	ft.	Size of watershed element
HU	in.	Maximum height of surface roughness influence on storage
NEXP	--	Drainage exponent used in infiltration calculations
ORIENT NO.	--	Watershed element orientation number.
PER	--	Ground surface covered by foliage--percent of total area
PIT	in.	Potential interception storage volume
ROUGH	--	Surface roughness category
RN	--	Manning's roughness coefficient

Table 15. Values of Variables Used to Simulate the Storm of June 12, 1957 on Watershed 115.

Trial No.	1	2	3	4	5	6	7	8	9	10	11	12
ADIR	0.02	0.02	0.04	0.04	0.04	0.04	0.162	0.162	0.162	0.162	0.162	0.162
ASM	50	50	50	60	40	40	40	50	10	10	10	10
DINF	5	5	5	5	5	7	16	16	16	16	16	16
DT	5	5	10	10	10	10	5	5	5	5	5	5
DX	40	40	40	40	40	40	50	50	50	50	40	50
HU	1	1	1	1	1	1	1	1	2	1	2	2
NEXP	3	3	3	3	3	3	3	3	3	3	3	3
ORIENT NO.	3	3	3	3	3	3	1	1	1	1	3	1
PER	70	70	70	70	70	70	70	70	70	70	70	70
PIT	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
ROUGH	4	4	4	4	4	4	2	2	2	2	2	2
RN	0.100	0.130	0.130	0.130	0.130	0.130	0.100	0.100	0.100	0.100	0.100	0.100

Table 16. Values of Variables Used to Simulate the Storm of April 25, 1961 on Watershed 115.

Trial No.	1	2	3	4	5	6	7
ADIR (in.)	0.02	0.02	0.10	0.06	0.04	0.01	0.01
ASM (%)	75	75	65	90	90	63	75
DINF (%)	5	5	3	3	5	5	5
DT (sec.)	5	5	5	10	10	10	10
DX (ft)	40	40	50	40	40	40	40
HU (in.)	1	1	1	1	1	1	1
NEXP	3	3	3	3	3	3	3
ORINET NO.	3	3	2	3	3	3	3
PER (%)	95	95	95	95	95	95	95
PIT (in.)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
ROUGH	4	4	2	4	4	4	4
RN	0.130	0.100	0.100	0.130	0.130	0.130	0.130

Results and Discussion

The results of the application of the storms of June 12, 1957 and April 25, 1961 to watershed 115 are shown in Table 17. The parameters used to obtain these results are shown in Tables 15 and 16. For the storm of of June 12, 1957 the predicted volume of runoff is consistently higher but the runoff rate and the time to peak are lower on the average. Several of the parameters like the surface retention depth, Manning's roughness coefficient, time increment, antecedent moisture condition, were varied but the predicted runoff volume did not improve sufficiently with these variations. In a few cases as the predicted peak runoff rate improved the runoff volume became worse and vise versa.

The predicted values of the runoff volume, the peak rate of runoff, and the time to peak were all higher for the storm of April 25, 1961 except that slightly lower values on the average were obtained for the rainfall amount of 1.58 inches. Figure 21 shows typical observed and predicted hydrographs for watershed 115 and for the storm of June 12, 1957. A similar plot for the same watershed is shown in Figure 22 for the storm of April 25, 1961.

On watershed 123 the predicted runoff volume was higher and the peak rate of runoff and the time to peak were lower for the storm of June 12, 1957.

Table 17. The Results of the Simulation of Watershed 115.

Trials	Observed Conditions				Predicted Conditions		
	Rainfall Amount in.	Runoff Volume in.	Runoff Peak Rate in/hr	Time to Peak min	Runoff Volume in.	Runoff Peak Rate in/hr	Time to Peak min
				Storm of June 12, 1957			
1	3.13	1.04	4.12	49	1.98	4.37	37.5
2	3.13	1.04	4.12	49	1.96	4.07	37.5
3	3.13	1.04	4.12	49	1.94	4.02	49.3
4	3.13	1.04	4.12	49	2.06	4.12	49.3
5	3.13	1.04	4.12	49	1.82	3.91	49.3
6	3.13	1.04	4.12	49	1.74	3.80	49.3
7	3.13	1.04	4.12	49	1.72	4.19	37.5
8	3.13	1.04	4.12	49	1.83	4.34	37.5
9	3.04	1.03	4.12	49	1.41	3.73	20.0
10	3.04	1.03	4.12	49	1.40	3.73	20.0
11	1.00	0.55	4.12	49	0.56	2.91	37.5
12	1.00	0.55	4.12	49	0.59	2.95	37.5
				Storm of April 25, 1961			
1	1.21	0.42	0.825	69	0.59	1.060	97.4
2	1.21	0.42	0.825	69	0.63	1.169	97.4
3	1.21	0.42	0.825	69	0.71	1.325	97.4
4	1.58	0.93	1.16	100	0.82	1.170	97.4
5	1.58	0.93	1.16	100	0.78	1.140	97.4
6	1.18	0.40	0.825	69	0.49	0.910	98.3
7	1.42	0.50	0.825	69	0.61	1.048	97.4

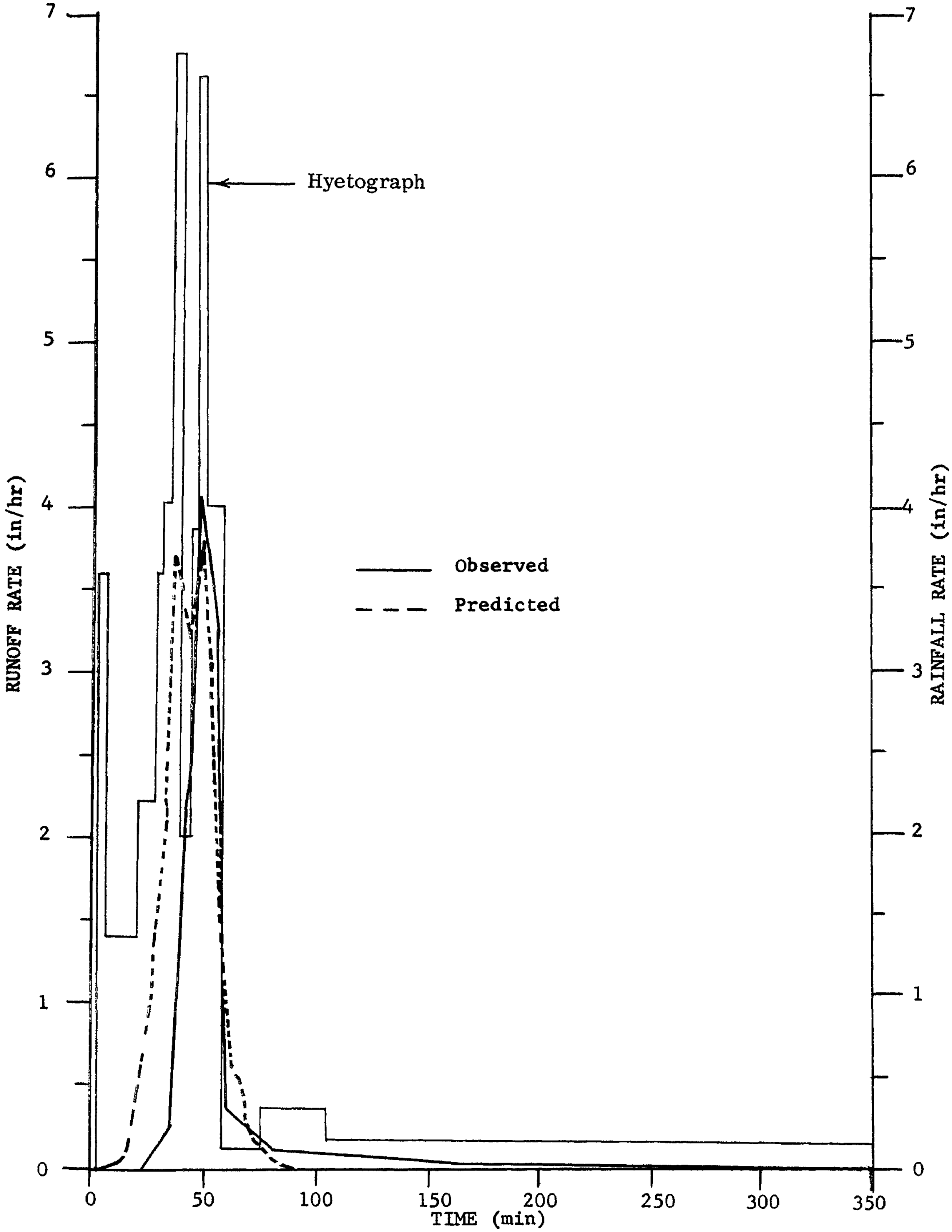

Figure 21. Observed and Predicted Hydrographs for Watershed 115 and the Storm of June 12, 1957.

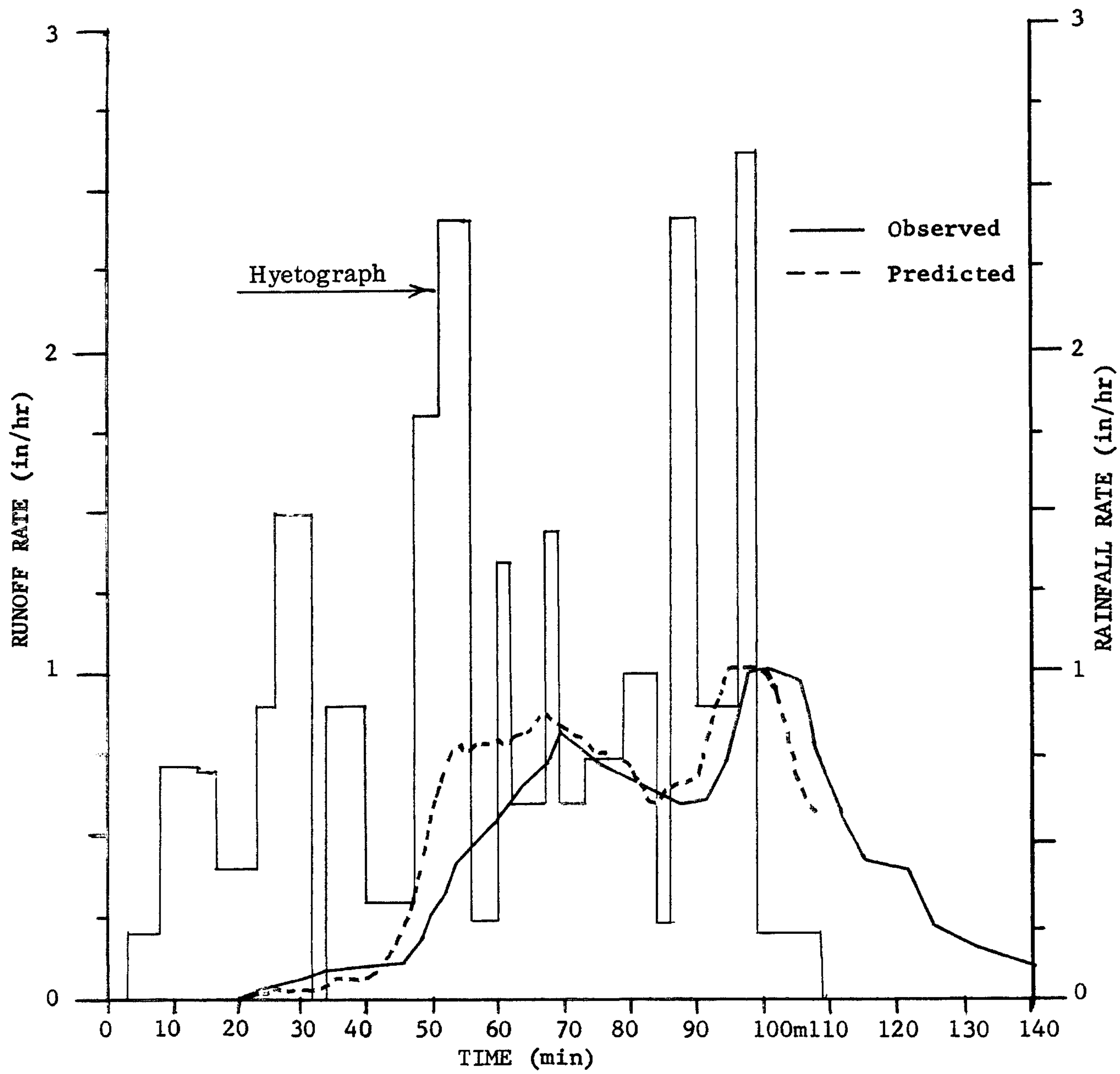

Figure 22. Observed and Predicted Hydrograph for Watershed 115 and the Storm of April 25, 1961.

But the storm of April 25, 1961 produced lower simulated runoff volume except the one inch of rainfall for which the predicted volume was higher. The simulated peak rate and the time to peak were higher for some trials and lower for others. These results are shown in Table 18. Figure 23 is a typical plot of the observed and predicted hydrographs for watershed 123 and the storm of April 25, 1961. The results of the simulation of watersheds 121 and 106 are shown in Tables 19 and 20.

In general the model tends to overpredict the runoff volume except for watersheds 106 and 121; for these two watersheds the simulated runoff volumes are less than the observed values for the storm of August 23, 1944. The predicted peak runoff rate and the time to peak are not nearly as consistent as the runoff volume; their values are higher for some trials and lower for others. It was, therefore, possible to adjust or improve the peak runoff rate and the time to peak by changing the values of the parameters; but these changes seldom produced runoff volumes which approached the observed values.

There will always be questions about the accuracy of a model of this nature or models in general unless accurate statements can be made about the antecedent conditions and the values of the parameters used.

This is not a continuous simulation model like the OSU and other versions of the Stanford watershed model but there is no question about its value in situations in which the volume of runoff, the peak rate, and the time to peak are required for small ungaged watersheds. More work still remains to be done with this model particularly with regards to better runoff and infiltration functions.

We cannot draw a definite conclusion as to the usefulness of the model for design purposes. This can only be done after it would have been applied to a wide range of watersheds under varying sets of conditions. The largest watershed we simulated was 1.61 acres; it will be useful to determine how far the model could be applied beyond this range. As it stands, this model still remains promising.

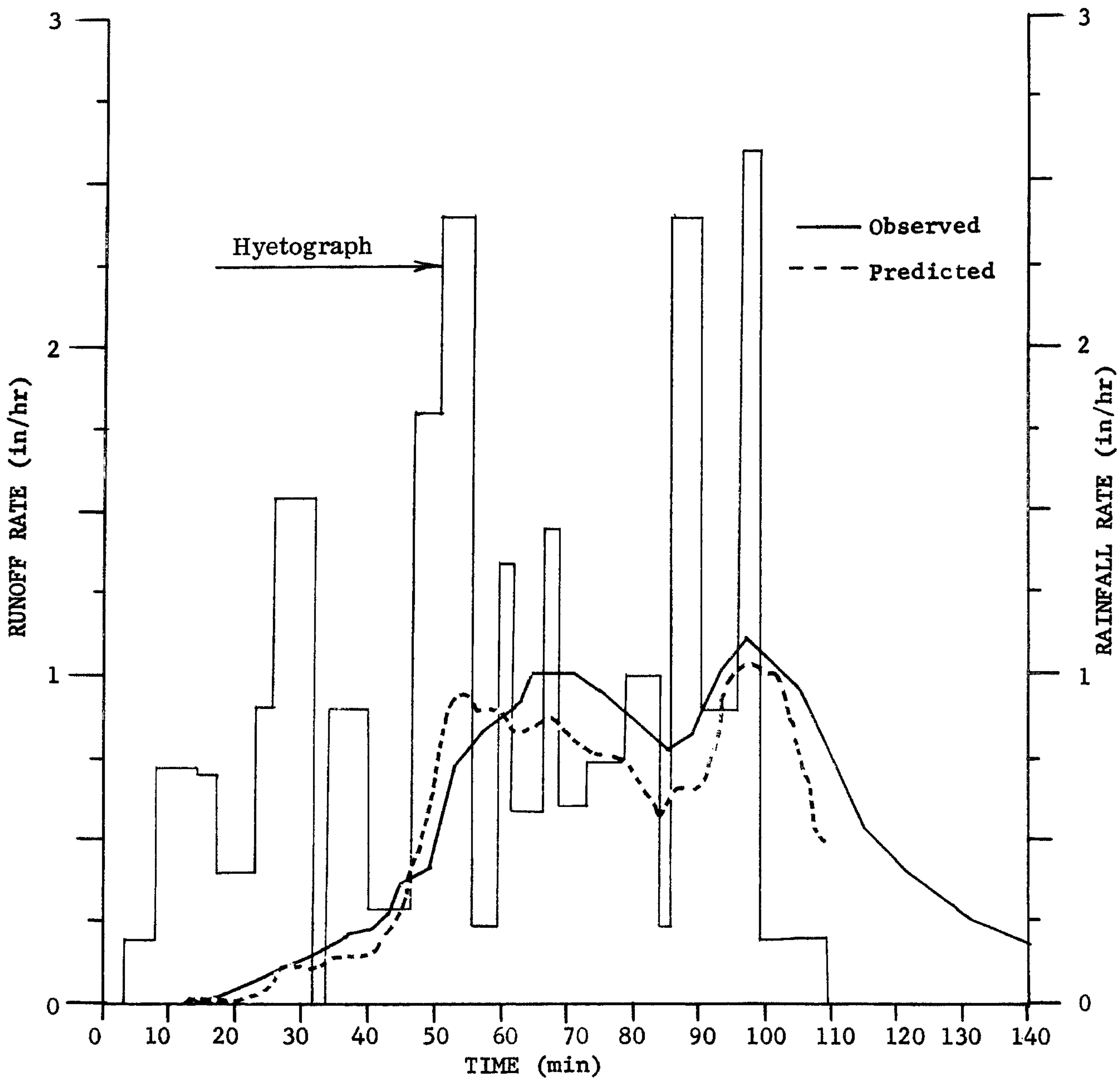

Figure 23. Observed and Predicted Hydrographs for Watershed 123 and the Storm of Ap4il 25, 1961

Table 18. The Results of the Simulation of Watershed 123.

Trial	Observed Conditions				Predicted Conditions		
	Rainfall Amount in.	Runoff Volume in.	Runoff Peak Rate in/hr	Time to Peak min.	Runoff Volume in.	Runoff Peak Rate in/hr	Time to Peak min.
				Storm of June 12, 1957			
1	3.13	1.50	5.97	50	1.999	4.561	37.3
2	3.13	1.50	5.97	50	1.958	4.241	37.3
3	3.13	1.50	5.97	50	2.058	4.386	37.3
4	3.13	1.50	5.97	50	1.918	4.237	37.3
5	1.00	0.11	3.20	45	0.64	2.978	20.0
6	3.04	1.47	5.97	50	1.853	4.448	37.5
				Storm of April 25, 1961			
1	1.60	0.96	1.23	97	0.90	1.239	96.7
2	1.60	0.96	1.23	97	0.84	1.207	96.7
3	1.18	0.67	1.03	65	0.51	0.974	98.3
4	1.18	0.67	1.03	65	0.51	1.331	96.7
5	1.21	0.69	1.03	65	0.66	1.235	97.1
6	1.00	0.41	1.03	65	0.71	2.948	20.0

Table 19. Results of the Simulation of Watershed 121.

Trial	Observed Conditions: Rainfall Amount in.	Observed Conditions: Runoff Volume in.	Observed Conditions: Runoff Peak Rates in/hr	Observed Conditions: Time to Peak min.	Predicted Conditions: Runoff Volume in.	Predicted Conditions: Runoff Peak Rate in/hr	Predicted Conditions: Time to Peak min.
			Storm of May 13, 1964				
1	1.31	0.393	2.430	19	0.562	2.253	21.0
2	1.31	0.393	2.430	19	0.717	4.141	17.5
3	1.00	0.001	2.430	19	0.741	2.998	20.0
			Storm of June 13, 1960				
1	3.45	0.376	1.655	489	1.222	1.332	415.3
2	3.45	0.376	1.655	489	1.577	2.407	379.1
			Storm of August 23, 1944				
1	1.22	1.0063	7.822	37	0.690	3.092	38.0
2	1.21	1.0063	7.822	37	0.849	5.257	37.0

Table 20. Results of the Simulation of Watershed 106.

Trial	Observed Conditions				Predicted Conditions		
	Rainfall Amount in.	Runoff Volume in.	Runoff Peak Rates in/hr	Time to Peak min.	Runoff Volume in.	Runoff Peak Rate in/hr	Time to Peak min.
				Storm of May 13, 1964			
1	1.31	0.299	2.339	19	0.650	4.060	18.6
2	1.31	0.299	2.339	19	0.697	4.593	17.2
3	1.00	0.0003	2.430	19	0.811	3.000	19.0
				Storm of June 13, 1960			
1	3.42	0.935	2.212	487	1.291	1.939	410.1
2	3.45	0.935	2.212	487	1.679	4.960	379.1
				Storm of August 23, 1944			
1	1.22	0.945	7.629	37	0.785	5.216	37.0
2	1.21	0.945	7.629	37	0.895	6.839	35.0

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